

(12) **United States Patent**  
**Rhodes et al.**

(10) **Patent No.:** **US 9,328,371 B2**  
(45) **Date of Patent:** **May 3, 2016**

(54) **SENSOR HEAD FOR USE WITH  
IMPLANTABLE DEVICES**

(56) **References Cited**

U.S. PATENT DOCUMENTS

1,564,641 A 12/1925 St. James  
2,402,306 A 6/1946 Turkel

(Continued)

FOREIGN PATENT DOCUMENTS

EP 0 098 592 1/1984  
EP 0 107 634 5/1984

(Continued)

OTHER PUBLICATIONS

Gross, Todd (2001), Diabetes Technology and Therapeutics 3(1): 130-131. Letters to the Editor re Diabetes Technology & Therapeutics 2000 2:49-56.

(Continued)

(71) Applicant: **DexCom, Inc.**, San Diego, CA (US)

(72) Inventors: **Rathbun K. Rhodes**, Madison, WI (US); **Mark A. Tapsak**, Orangeville, PA (US); **James H. Brauker**, Cement City, MI (US); **Mark C. Shults**, Madison, WI (US)

(73) Assignee: **DexCom, Inc.**, San Diego, CA (US)

(\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 34 days.

(21) Appl. No.: **13/943,622**

(22) Filed: **Jul. 16, 2013**

(65) **Prior Publication Data**

US 2013/0299350 A1 Nov. 14, 2013

**Related U.S. Application Data**

(60) Continuation of application No. 12/260,017, filed on Oct. 28, 2008, now Pat. No. 8,509,871, which is a division of application No. 11/021,162, filed on Dec. 22, 2004, now Pat. No. 7,471,972, which is a continuation of application No. 09/916,711, filed on Jul. 27, 2001, now abandoned.

(51) **Int. Cl.**

**A61B 5/05** (2006.01)

**A61B 5/00** (2006.01)

(Continued)

(52) **U.S. Cl.**

CPC ..... **C12Q 1/006** (2013.01); **A61B 5/14532** (2013.01); **A61B 5/14865** (2013.01); **C12Q 1/002** (2013.01)

(58) **Field of Classification Search**

CPC ..... A61B 5/14532

USPC ..... 600/309, 345-347, 365

See application file for complete search history.

*Primary Examiner* — Christian Jang

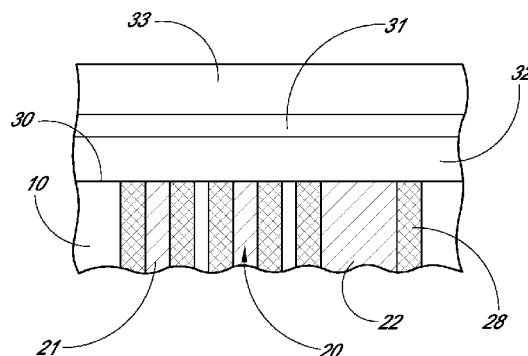
(74) *Attorney, Agent, or Firm* — Knobbe Martens Olson & Bear, LLP

(57)

**ABSTRACT**

The present invention provides a sensor head for use in an implantable device that measures the concentration of an analyte in a biological fluid which includes: a non-conductive body; a working electrode, a reference electrode and a counter electrode, wherein the electrodes pass through the non-conductive body forming an electrochemically reactive surface at one location on the body and forming an electronic connection at another location on the body, further wherein the electrochemically reactive surface of the counter electrode is greater than the surface area of the working electrode; and a multi-region membrane affixed to the nonconductive body and covering the working electrode, reference electrode and counter electrode. In addition, the present invention provides an implantable device including at least one of the sensor heads of the invention and methods of monitoring glucose levels in a host utilizing the implantable device of the invention.

**7 Claims, 15 Drawing Sheets**



(51)	<b>Int. Cl.</b>		4,571,292 A	2/1986	Liu et al.
	<b>C12Q 1/00</b>		4,577,642 A	3/1986	Stokes
	<b>A61B 5/145</b>		4,578,215 A	3/1986	Bradley
	<b>A61B 5/1486</b>		4,583,976 A	4/1986	Ferguson
			4,602,922 A	7/1986	Cabasso et al.
			4,632,968 A	12/1986	Yokota et al.
			4,644,046 A	2/1987	Yamada
			4,647,643 A	3/1987	Zdrahala et al.
(56)	<b>References Cited</b>		4,650,547 A	3/1987	Gough
	<b>U.S. PATENT DOCUMENTS</b>		4,655,880 A	4/1987	Liu
	2,719,797 A	10/1955 Rosenblatt et al.	4,663,824 A	5/1987	Kenmochi
	2,830,020 A	4/1958 Christmann et al.	4,671,288 A	6/1987	Gough
	3,210,578 A	10/1965 Sherer	4,672,970 A	6/1987	Uchida et al.
	3,220,960 A	11/1965 Drahoslav Lim et al.	4,680,268 A	7/1987	Clark, Jr.
	3,381,371 A	5/1968 Russell	4,684,538 A	8/1987	Klemarczyk
	3,562,352 A	2/1971 Nyilas	4,685,463 A	8/1987	Williams
	3,607,329 A	9/1971 Manjikian	4,686,044 A	8/1987	Behnke et al.
	3,652,475 A	3/1972 Wada et al.	4,686,137 A	8/1987	Ward, Jr. et al.
	3,746,588 A	7/1973 Brown, Jr.	4,689,149 A	8/1987	Kanno et al.
	3,775,182 A	11/1973 Patton et al.	4,689,309 A	8/1987	Jones
	3,791,871 A	2/1974 Rowley	4,702,732 A	10/1987	Powers et al.
	3,826,244 A	7/1974 Salcman et al.	4,703,756 A	11/1987	Gough et al.
	3,838,033 A	9/1974 Mindt et al.	4,711,245 A	12/1987	Higgins
	3,898,984 A	8/1975 Mandel et al.	4,711,251 A	12/1987	Stokes
	3,929,971 A	12/1975 Roy	4,721,677 A	1/1988	Clark, Jr.
	3,933,593 A	1/1976 Sternberg	4,726,381 A	2/1988	Jones
	3,943,918 A	3/1976 Lewis	4,731,726 A	3/1988	Allen
	3,957,613 A	5/1976 Macur	4,739,380 A	4/1988	Lauks et al.
	3,964,974 A	6/1976 Banauch et al.	4,750,496 A	6/1988	Reinhart et al.
	3,966,580 A	6/1976 Janata et al.	4,753,652 A	6/1988	Langer et al.
	3,979,274 A	9/1976 Newman	4,757,022 A	7/1988	Shults et al.
	3,982,530 A	9/1976 Storch	4,759,828 A	7/1988	Young et al.
	4,024,312 A	5/1977 Korpman	4,763,658 A	8/1988	Jones
	4,037,563 A	7/1977 Pflueger et al.	4,776,944 A	10/1988	Janata et al.
	4,040,908 A	8/1977 Clark, Jr.	4,781,733 A	11/1988	Babcock et al.
	4,052,754 A	10/1977 Homsy	4,781,798 A	11/1988	Gough
	4,067,322 A	1/1978 Johnson	4,786,657 A	11/1988	Hammar et al.
	4,073,713 A	2/1978 Newman	4,787,398 A	11/1988	Garcia et al.
	4,076,656 A	2/1978 White et al.	4,793,555 A	12/1988	Lee et al.
	4,136,250 A	1/1979 Mueller et al.	4,795,542 A	1/1989	Ross et al.
	4,172,770 A	10/1979 Semersky et al.	4,803,243 A	2/1989	Fujimoto et al.
	4,197,840 A	4/1980 Beck et al.	4,805,624 A	2/1989	Yao et al.
	4,215,703 A	8/1980 Willson	4,805,625 A	2/1989	Wyler
	4,240,889 A	12/1980 Yoda et al.	4,810,470 A	3/1989	Burkhardt et al.
	4,253,469 A	3/1981 Aslan	4,813,424 A	3/1989	Wilkins
	4,255,500 A	3/1981 Hooke	4,822,336 A	4/1989	DiTraglia
	4,256,561 A	3/1981 Schindler et al.	4,823,808 A	4/1989	Clegg et al.
	4,259,540 A	3/1981 Sabia	4,832,034 A	5/1989	Pizziconi
	4,260,725 A	4/1981 Keogh et al.	4,852,573 A	8/1989	Kennedy
	4,267,145 A	5/1981 Wysong	4,858,615 A	8/1989	Meinema
	4,292,423 A	9/1981 Kaufmann et al.	4,861,830 A	8/1989	Ward, Jr.
	4,324,257 A	4/1982 Albarda et al.	4,871,440 A	10/1989	Nagata et al.
	4,353,888 A	10/1982 Sefton	4,880,883 A	11/1989	Grasel et al.
	4,374,013 A	2/1983 Enfors	4,883,057 A	11/1989	Broderick
	4,378,016 A	3/1983 Loeb	4,886,740 A	12/1989	Vadgama
	4,388,166 A	6/1983 Suzuki et al.	4,889,744 A	12/1989	Quaid
	4,402,694 A	9/1983 Ash et al.	4,890,620 A	1/1990	Gough
	4,403,847 A	9/1983 Chrestensen	4,890,621 A	1/1990	Hakky
	4,403,984 A	9/1983 Ash et al.	4,902,294 A	2/1990	Gosserez
	4,415,666 A	11/1983 D'Orazio et al.	4,908,208 A	3/1990	Lee et al.
	4,418,148 A	11/1983 Oberhardt	4,909,908 A	3/1990	Ross et al.
	4,419,535 A	12/1983 O'hara	4,919,141 A	4/1990	Zier et al.
	4,431,004 A	2/1984 Bessman et al.	4,927,407 A	5/1990	Dorman
	4,431,507 A	2/1984 Nankai et al.	4,935,345 A	6/1990	Guilbeau et al.
	4,436,094 A	3/1984 Cerami	4,938,860 A	7/1990	Wogoman
	4,442,841 A	4/1984 Uehara et al.	4,951,657 A	8/1990	Pfister et al.
	4,453,537 A	6/1984 Spitzer	4,952,618 A	8/1990	Olsen
	4,454,295 A	6/1984 Wittmann et al.	4,953,552 A	9/1990	DeMarzo
	4,477,314 A	10/1984 Richter et al.	4,954,381 A	9/1990	Cabasso et al.
	4,482,666 A	11/1984 Reeves	4,955,861 A	9/1990	Enegren et al.
	4,484,987 A	11/1984 Gough	4,958,148 A	9/1990	Olson
	4,493,714 A	1/1985 Ueda et al.	4,960,594 A	10/1990	Honeycutt
	4,494,950 A	1/1985 Fischell	4,961,954 A	10/1990	Goldberg et al.
	4,506,680 A	3/1985 Stokes	4,963,595 A	10/1990	Ward et al.
	RE31,916 E	6/1985 Oswin et al.	4,970,145 A	11/1990	Bennetto et al.
	4,527,999 A	7/1985 Lee	4,973,320 A	11/1990	Brenner et al.
	4,534,355 A	8/1985 Potter	4,974,929 A	12/1990	Curry
	4,545,382 A	10/1985 Higgins et al.	4,975,175 A	12/1990	Karube et al.
	4,554,927 A	11/1985 Fussell	4,984,929 A	1/1991	Rock et al.

(56)

## References Cited

## U.S. PATENT DOCUMENTS

4,986,671 A	1/1991	Sun et al.	5,340,352 A	8/1994	Nakanishi et al.
4,988,341 A	1/1991	Columbus et al.	5,342,409 A	8/1994	Mullett
4,988,758 A	1/1991	Fukuda et al.	5,342,693 A	8/1994	Winters et al.
4,992,794 A	2/1991	Brouwers	5,343,869 A	9/1994	Pross et al.
4,994,167 A	2/1991	Shults et al.	5,344,454 A	9/1994	Clarke et al.
5,002,572 A	3/1991	Picha	5,348,788 A	9/1994	White
5,002,590 A	3/1991	Friesen et al.	5,352,348 A	10/1994	Young et al.
5,007,929 A	4/1991	Quaid	5,352,351 A	10/1994	White
5,010,141 A	4/1991	Mueller	5,354,449 A	10/1994	Band et al.
5,034,112 A	7/1991	Murase et al.	5,356,786 A	10/1994	Heller et al.
5,034,461 A	7/1991	Lai et al.	5,372,133 A	12/1994	Hogen Esch
5,045,601 A	9/1991	Capelli et al.	5,376,400 A	12/1994	Goldberg et al.
5,050,612 A	9/1991	Matsumura	5,380,536 A	1/1995	Hubbell et al.
5,059,654 A	10/1991	Hou et al.	5,384,028 A	1/1995	Ito
5,063,081 A	11/1991	Cozzette et al.	5,387,327 A	2/1995	Khan
5,067,491 A	11/1991	Taylor, II et al.	5,390,671 A	2/1995	Lord et al.
5,070,169 A	12/1991	Robertson et al.	5,391,250 A	2/1995	Cheney, II et al.
5,071,452 A	12/1991	Avrillon et al.	5,397,451 A	3/1995	Senda et al.
5,089,112 A	2/1992	Skotheim et al.	5,397,848 A	3/1995	Yang et al.
5,094,876 A	3/1992	Goldberg et al.	5,411,647 A	5/1995	Johnson et al.
5,100,689 A	3/1992	Goldberg et al.	5,411,866 A	5/1995	Luong
5,101,814 A	4/1992	Palti	5,417,395 A	5/1995	Fowler et al.
5,108,819 A	4/1992	Heller et al.	5,421,923 A	6/1995	Clarke et al.
5,113,871 A	5/1992	Viljanto et al.	5,425,717 A	6/1995	Mohiuddin
5,115,056 A	5/1992	Mueller et al.	5,426,158 A	6/1995	Mueller et al.
5,120,813 A	6/1992	Ward, Jr.	5,428,123 A	6/1995	Ward et al.
5,128,408 A	7/1992	Tanaka et al.	5,429,735 A	7/1995	Johnson et al.
5,135,297 A	8/1992	Valint et al.	5,431,160 A	7/1995	Wilkins
5,137,028 A	8/1992	Nishimura	5,438,984 A	8/1995	Schoendorfer
5,147,725 A	9/1992	Pinchuk	5,453,278 A	9/1995	Chan et al.
5,155,149 A	10/1992	Atwater et al.	5,462,051 A	10/1995	Oka et al.
5,160,418 A	11/1992	Mullen	5,462,064 A	10/1995	D'Angelo et al.
5,165,407 A	11/1992	Wilson et al.	5,462,645 A	10/1995	Albery et al.
5,169,906 A	12/1992	Cray et al.	5,466,356 A	11/1995	Schneider et al.
5,171,689 A	12/1992	Kawaguri et al.	5,466,575 A	11/1995	Cozzette et al.
5,183,549 A	2/1993	Joseph et al.	5,469,846 A	11/1995	Khan
5,190,041 A	3/1993	Palti	5,474,552 A	12/1995	Palti
5,200,051 A	4/1993	Cozzette et al.	5,476,094 A	12/1995	Allen et al.
5,202,261 A	4/1993	Musho et al.	5,476,776 A	12/1995	Wilkins
5,208,313 A	5/1993	Krishnan	5,482,008 A	1/1996	Stafford et al.
5,212,050 A	5/1993	Mier et al.	5,482,473 A	1/1996	Lord et al.
5,219,965 A	6/1993	Valint et al.	5,484,404 A	1/1996	Schulman et al.
5,221,724 A	6/1993	Li et al.	5,491,474 A	2/1996	Suni et al.
5,235,003 A	8/1993	Ward et al.	5,494,562 A	2/1996	Maley et al.
5,242,835 A	9/1993	Jensen	5,496,453 A	3/1996	Uenoyama et al.
5,243,696 A	9/1993	Carr et al.	5,497,772 A	3/1996	Schulman et al.
5,249,576 A	10/1993	Goldberger et al.	5,502,396 A	3/1996	Desarzens et al.
5,250,439 A	10/1993	Musho et al.	5,507,288 A	4/1996	Bocker et al.
5,264,104 A	11/1993	Gregg et al.	5,508,509 A	4/1996	Yafuso et al.
5,266,179 A	11/1993	Nankai et al.	5,513,636 A	5/1996	Palti
5,269,891 A	12/1993	Colin	5,518,601 A	5/1996	Foos et al.
5,271,736 A	12/1993	Picha	5,521,273 A	5/1996	Yilgor et al.
5,281,319 A	1/1994	Kaneko et al.	5,531,878 A	7/1996	Vadgama et al.
5,282,848 A	2/1994	Schmitt	5,538,511 A	7/1996	Van Antwerp
5,284,140 A	2/1994	Allen et al.	5,540,828 A	7/1996	Yacynych
5,285,513 A	2/1994	Kaufman et al.	5,541,305 A	7/1996	Yokota et al.
5,286,364 A	2/1994	Yacynych et al.	5,545,220 A	8/1996	Andrews et al.
5,296,144 A	3/1994	Sternina et al.	5,545,223 A	8/1996	Neuenfeldt et al.
5,298,144 A	3/1994	Spokane	5,549,675 A	8/1996	Neuenfeldt et al.
5,299,571 A	4/1994	Mastrototaro	5,552,112 A	9/1996	Schiffmann
5,304,468 A	4/1994	Phillips et al.	5,554,339 A	9/1996	Cozzette
5,307,263 A	4/1994	Brown	5,564,439 A	10/1996	Picha
5,310,469 A	5/1994	Cunningham et al.	5,568,806 A	10/1996	Cheney, II et al.
5,312,361 A	5/1994	Zadini et al.	5,569,186 A	10/1996	Lord et al.
5,314,471 A	5/1994	Brauker et al.	5,569,462 A	10/1996	Martinson et al.
5,316,008 A	5/1994	Suga et al.	5,571,395 A	11/1996	Park et al.
5,321,414 A	6/1994	Alden et al.	5,575,930 A	11/1996	Tietje-Girault et al.
5,322,063 A	6/1994	Allen et al.	5,578,463 A	11/1996	Berka et al.
5,324,322 A	6/1994	Grill et al.	5,582,184 A	12/1996	Erickson et al.
5,326,356 A	7/1994	Della Valle et al.	5,582,697 A	12/1996	Ikeda et al.
5,330,521 A	7/1994	Cohen	5,584,813 A	12/1996	Livingston et al.
5,330,634 A	7/1994	Wong et al.	5,584,876 A	12/1996	Bruchman et al.
5,331,555 A	7/1994	Hashimoto et al.	5,586,553 A	12/1996	Halili et al.
5,334,681 A	8/1994	Mueller et al.	5,588,560 A	12/1996	Benedict et al.
5,337,747 A	8/1994	Neftel	5,589,133 A	12/1996	Suzuki
			5,589,563 A	12/1996	Ward et al.
			5,590,651 A	1/1997	Shaffer et al.
			5,593,440 A	1/1997	Brauker et al.
			5,593,852 A	1/1997	Heller et al.

(56)

## References Cited

## U.S. PATENT DOCUMENTS

5,607,565 A	3/1997	Azarnia et al.	5,897,578 A	4/1999	Wiklund et al.
5,611,900 A	3/1997	Worden	5,897,955 A	4/1999	Drumheller
5,624,537 A	4/1997	Turner et al.	5,904,708 A	5/1999	Goedeke
5,628,890 A	5/1997	Carter et al.	5,910,554 A	6/1999	Kempe et al.
5,640,954 A	6/1997	Pfeiffer et al.	5,913,998 A	6/1999	Butler et al.
5,653,756 A	8/1997	Clarke et al.	5,914,026 A	6/1999	Blubaugh, Jr. et al.
5,653,863 A	8/1997	Genshaw et al.	5,914,182 A	6/1999	Drumheller
5,658,330 A	8/1997	Carlisle et al.	5,917,346 A	6/1999	Gord
5,660,163 A	8/1997	Schulman et al.	5,919,215 A	7/1999	Wiklund et al.
5,665,222 A	9/1997	Heller et al.	5,928,130 A	7/1999	Schmidt
5,670,097 A	9/1997	Duan et al.	5,931,814 A	8/1999	Alex et al.
5,676,820 A	10/1997	Wang et al.	5,932,299 A	8/1999	Katoot
5,682,884 A	11/1997	Hill	5,944,661 A	8/1999	Swette et al.
5,683,562 A	11/1997	Schaffar et al.	5,945,498 A	8/1999	Hopken et al.
5,686,829 A	11/1997	Girault	5,947,127 A	9/1999	Tsugaya et al.
5,695,623 A	12/1997	Michel et al.	5,954,643 A	9/1999	VanAntwerp et al.
5,700,559 A	12/1997	Sheu et al.	5,954,954 A	9/1999	Houck et al.
5,703,359 A	12/1997	Wampler, III	5,955,066 A	9/1999	Sako et al.
5,704,354 A	1/1998	Priedel et al.	5,957,854 A	9/1999	Besson et al.
5,706,807 A	1/1998	Picha	5,957,903 A	9/1999	Mirzaee et al.
5,707,502 A	1/1998	McCaffrey et al.	5,959,191 A	9/1999	Lewis et al.
5,711,861 A	1/1998	Ward et al.	5,961,451 A	10/1999	Reber et al.
5,713,888 A	2/1998	Neuenfeldt et al.	5,963,132 A	10/1999	Yoakum
5,733,336 A	3/1998	Neuenfeldt et al.	5,964,261 A	10/1999	Neuenfeldt et al.
5,735,273 A	4/1998	Kurnik et al.	5,964,804 A	10/1999	Brauker et al.
5,738,902 A	4/1998	Forrestal et al.	5,964,993 A	10/1999	Blubaugh et al.
5,741,330 A	4/1998	Brauker et al.	5,965,380 A	10/1999	Heller et al.
5,741,634 A	4/1998	Nozoe et al.	5,969,076 A	10/1999	Lai et al.
5,743,262 A	4/1998	Lepper, Jr. et al.	5,972,199 A	10/1999	Heller
5,746,898 A	5/1998	Priedel	5,976,085 A	11/1999	Kimball et al.
5,749,832 A	5/1998	Vadgama et al.	5,977,241 A	11/1999	Koloski et al.
5,756,632 A	5/1998	Ward et al.	5,985,129 A	11/1999	Gough et al.
5,760,155 A	6/1998	Mowrer et al.	5,989,409 A	11/1999	Kurnik et al.
5,766,151 A	6/1998	Valley et al.	5,999,848 A	12/1999	Gord et al.
5,766,839 A	6/1998	Johnson et al.	6,001,067 A	12/1999	Shults et al.
5,776,324 A	7/1998	Usala	6,001,471 A	12/1999	Bries et al.
5,777,060 A	7/1998	Van Antwerp	6,002,954 A	12/1999	Van Antwerp et al.
5,779,665 A	7/1998	Mastrototaro et al.	6,007,845 A	12/1999	Domb
5,782,912 A	7/1998	Brauker et al.	6,011,984 A	1/2000	Van Antwerp et al.
5,783,054 A	7/1998	Raguse et al.	6,013,113 A	1/2000	Mika
5,786,439 A	7/1998	Van Antwerp et al.	6,016,448 A	1/2000	Busacker et al.
5,787,900 A	8/1998	Butler et al.	6,018,013 A	1/2000	Yoshida et al.
5,791,344 A	8/1998	Schulman et al.	6,018,033 A	1/2000	Chen et al.
5,795,453 A	8/1998	Gilmartin	6,022,463 A	2/2000	Leader et al.
5,795,774 A	8/1998	Matsumoto et al.	6,030,827 A	2/2000	Davis et al.
5,798,065 A	8/1998	Picha	6,039,913 A	3/2000	Hirt et al.
5,800,420 A	9/1998	Gross	6,043,328 A	3/2000	Domschke et al.
5,800,529 A	9/1998	Brauker et al.	6,049,727 A	4/2000	Crothall
5,804,048 A	9/1998	Wong et al.	6,051,389 A	4/2000	Ahl et al.
5,807,375 A	9/1998	Gross	6,059,946 A	5/2000	Yukawa et al.
5,807,406 A	9/1998	Brauker et al.	6,063,637 A	5/2000	Arnold et al.
5,807,636 A	9/1998	Sheu et al.	6,066,083 A	5/2000	Slater et al.
5,811,487 A	9/1998	Schulz, Jr. et al.	6,066,448 A	5/2000	Wohlstadter et al.
5,820,570 A	10/1998	Erickson	6,071,406 A	6/2000	Tsou
5,820,622 A	10/1998	Gross et al.	6,074,775 A	6/2000	Gartstein et al.
5,823,802 A	10/1998	Bartley	6,081,736 A	6/2000	Colvin et al.
5,833,603 A	11/1998	Kovacs et al.	6,083,710 A	7/2000	Heller et al.
5,834,583 A	11/1998	Hancock et al.	6,088,608 A	7/2000	Schulman et al.
5,837,377 A	11/1998	Sheu et al.	6,091,975 A	7/2000	Daddona et al.
5,837,454 A	11/1998	Cozzette et al.	6,093,156 A	7/2000	Cunningham et al.
5,837,661 A	11/1998	Evans et al.	6,093,172 A	7/2000	Funderburk et al.
5,837,728 A	11/1998	Purcell	6,103,033 A	8/2000	Say
5,840,148 A	11/1998	Campbell et al.	6,115,634 A	9/2000	Donders et al.
5,840,240 A	11/1998	Stenoien et al.	6,117,290 A	9/2000	Say et al.
5,843,069 A	12/1998	Butler et al.	6,119,028 A	9/2000	Schulman et al.
5,851,197 A	12/1998	Marano et al.	6,121,009 A	9/2000	Heller et al.
5,861,019 A	1/1999	Sun et al.	6,122,536 A	9/2000	Sun et al.
5,863,400 A	1/1999	Drummond et al.	6,134,461 A	10/2000	Say et al.
5,863,972 A	1/1999	Beckelmann et al.	6,135,978 A	10/2000	Houben et al.
5,871,514 A	2/1999	Wiklund et al.	6,144,869 A	11/2000	Berner et al.
5,879,373 A	3/1999	Roper et al.	6,144,871 A	11/2000	Saito et al.
5,882,354 A	3/1999	Brauker et al.	6,162,611 A	12/2000	Heller et al.
5,882,494 A	3/1999	Van Antwerp	6,167,614 B1	1/2001	Tuttle et al.
5,885,566 A	3/1999	Goldberg	6,169,155 B1	1/2001	Alvarez et al.
5,895,235 A	4/1999	Droz	6,175,752 B1 *	1/2001	Say et al. .... 600/345
			6,180,416 B1	1/2001	Kurnik et al.
			6,187,062 B1	2/2001	Oweis et al.
			6,189,536 B1	2/2001	Martinez et al.
			6,200,772 B1	3/2001	Vadgama et al.

(56)

## References Cited

## U.S. PATENT DOCUMENTS

6,201,980 B1	3/2001	Darrow et al.	6,510,329 B2	1/2003	Heckel
6,206,856 B1	3/2001	Mahurkar	6,512,939 B1	1/2003	Colvin et al.
6,208,894 B1	3/2001	Schulman et al.	6,514,718 B2	2/2003	Heller et al.
6,212,416 B1	4/2001	Ward et al.	6,520,326 B2	2/2003	McIvor et al.
6,212,417 B1 *	4/2001	Ikeda et al. .... 204/403.14	6,520,997 B1	2/2003	Pekkarinen et al.
6,214,185 B1	4/2001	Offenbacher et al.	6,527,729 B1	3/2003	Turcott
6,223,083 B1	4/2001	Rosar	6,528,584 B2	3/2003	Kennedy et al.
6,230,059 B1	5/2001	Duffin	6,534,711 B1	3/2003	Pollack
6,231,879 B1	5/2001	Li et al.	6,537,318 B1	3/2003	Ita et al.
6,233,471 B1	5/2001	Berner et al.	6,541,107 B1	4/2003	Zhong et al.
6,241,863 B1	6/2001	Monbouquette	6,545,085 B2	4/2003	Kilgour et al.
6,248,067 B1	6/2001	Causey, III et al.	6,546,268 B1	4/2003	Ishikawa et al.
6,254,586 B1	7/2001	Mann et al.	6,547,839 B2	4/2003	Zhang et al.
6,255,592 B1	7/2001	Pennington et al.	6,551,496 B1	4/2003	Moles et al.
6,256,522 B1	7/2001	Schultz	6,553,241 B2	4/2003	Mannheimer et al.
6,259,937 B1	7/2001	Schulman et al.	6,554,982 B1	4/2003	Shin et al.
6,264,825 B1	7/2001	Blackburn et al.	6,558,320 B1	5/2003	Causey
6,268,161 B1	7/2001	Han et al.	6,558,321 B1	5/2003	Burd et al.
6,271,332 B1	8/2001	Lohmann et al.	6,558,351 B1	5/2003	Steil et al.
6,272,364 B1	8/2001	Kurnik	6,560,471 B1	5/2003	Heller et al.
6,272,382 B1	8/2001	Faltys et al.	6,565,509 B1	5/2003	Plante et al.
6,274,285 B1	8/2001	Gries et al.	6,569,309 B2	5/2003	Otsuka et al.
6,275,717 B1	8/2001	Gross et al.	6,569,521 B1	5/2003	Sheridan et al.
6,284,478 B1	9/2001	Heller et al.	6,579,498 B1	6/2003	Eglise
6,285,897 B1	9/2001	Kilcoyne et al.	6,584,335 B1	6/2003	Haar et al.
6,293,925 B1	9/2001	Safabash et al.	6,585,763 B1	7/2003	Keilman et al.
6,294,281 B1	9/2001	Heller	6,591,125 B1	7/2003	Buse et al.
6,299,578 B1	10/2001	Kurnik et al.	6,596,294 B2	7/2003	Lai et al.
6,300,002 B1	10/2001	Webb et al.	6,607,509 B2	8/2003	Bobroff et al.
6,303,670 B1	10/2001	Fujino et al.	6,612,984 B1	9/2003	Kerr
6,306,594 B1	10/2001	Cozzette	6,613,379 B2	9/2003	Ward et al.
6,309,351 B1	10/2001	Kurnik et al.	6,615,078 B1	9/2003	Burson et al.
6,309,384 B1	10/2001	Harrington et al.	6,618,934 B1	9/2003	Feldman et al.
6,309,526 B1	10/2001	Fujiwara et al.	6,633,772 B2	10/2003	Ford et al.
6,312,706 B1	11/2001	Lai et al.	6,642,015 B2	11/2003	Vachon et al.
6,325,978 B1	12/2001	Labuda et al.	6,645,181 B1	11/2003	Lavi et al.
6,325,979 B1	12/2001	Hahn et al.	6,648,821 B2	11/2003	Lebel et al.
6,326,160 B1	12/2001	Dunn et al.	6,654,625 B1	11/2003	Say et al.
6,329,161 B1	12/2001	Heller et al.	6,666,821 B2	12/2003	Keimel
6,329,488 B1	12/2001	Terry et al.	6,670,115 B1	12/2003	Zhang
6,330,464 B1	12/2001	Colvin, Jr. et al.	6,683,535 B1	1/2004	Utke
6,343,225 B1	1/2002	Clark, Jr.	6,689,265 B2	2/2004	Heller et al.
6,358,557 B1	3/2002	Wang et al.	6,694,191 B2	2/2004	Starkweather et al.
6,360,888 B1	3/2002	McIvor et al.	6,695,860 B1	2/2004	Ward et al.
6,365,670 B1	4/2002	Fry	6,699,218 B2	3/2004	Flaherty et al.
6,366,794 B1	4/2002	Moussy et al.	6,699,383 B2	3/2004	Lemire et al.
6,368,141 B1	4/2002	VanAntwerp et al.	6,702,857 B2	3/2004	Brauker et al.
6,368,274 B1	4/2002	Van Antwerp et al.	6,702,972 B1	3/2004	Markle
6,368,658 B1	4/2002	Schwarz et al.	6,721,587 B2	4/2004	Gough
6,372,244 B1	4/2002	Antanavich et al.	6,730,200 B1	5/2004	Stewart et al.
6,387,379 B1	5/2002	Goldberg et al.	6,731,976 B2	5/2004	Penn et al.
6,400,974 B1	6/2002	Lesho	6,733,655 B1	5/2004	Davies et al.
6,405,066 B1	6/2002	Essenpreis et al.	6,737,158 B1	5/2004	Thompson
6,406,066 B1	6/2002	Uegane	6,740,075 B2	5/2004	Lebel et al.
6,407,195 B2	6/2002	Sherman et al.	6,741,877 B1	5/2004	Shults et al.
6,409,674 B1	6/2002	Brockway et al.	6,743,635 B2	6/2004	Neel et al.
6,413,393 B1	7/2002	Van Antwerp et al.	6,773,565 B2	8/2004	Kunimoto et al.
6,418,332 B1	7/2002	Mastrototaro et al.	6,784,274 B2	8/2004	van Antwerp et al.
6,424,847 B1	7/2002	Mastrototaro et al.	6,789,634 B1	9/2004	Denton
6,442,413 B1	8/2002	Silver	6,793,789 B2	9/2004	Choi et al.
6,447,448 B1	9/2002	Ishikawa et al.	6,793,802 B2	9/2004	Lee et al.
6,447,542 B1	9/2002	Waddock	6,801,041 B2	10/2004	Karinka et al.
6,454,710 B1	9/2002	Ballerstadt et al.	6,802,957 B2	10/2004	Jung et al.
6,459,917 B1	10/2002	Gowda et al.	6,809,653 B1	10/2004	Mann et al.
6,461,496 B1	10/2002	Feldman et al.	6,810,290 B2	10/2004	Lebel et al.
6,466,810 B1 *	10/2002	Ward et al. .... 600/345	6,858,218 B2	2/2005	Lai et al.
6,471,689 B1	10/2002	Joseph et al.	6,862,465 B2	3/2005	Shults et al.
6,475,750 B1	11/2002	Han et al.	6,867,262 B1	3/2005	Angel et al.
6,477,392 B1	11/2002	Honigs et al.	6,881,551 B2	4/2005	Heller et al.
6,477,395 B2	11/2002	Schulman et al.	6,892,085 B2	5/2005	McIvor et al.
6,481,440 B2	11/2002	Gielen et al.	6,893,552 B1	5/2005	Wang et al.
6,484,045 B1	11/2002	Holker et al.	6,895,263 B2	5/2005	Shin et al.
6,484,046 B1	11/2002	Say et al.	6,895,265 B2	5/2005	Silver
6,498,043 B1	12/2002	Schulman et al.	6,908,681 B2	6/2005	Terry et al.
6,498,941 B1	12/2002	Jackson	6,932,894 B2	8/2005	Mao et al.
			6,952,604 B2	10/2005	DeNuzzio et al.
			6,965,791 B1	11/2005	Hitchcock et al.
			6,969,451 B2	11/2005	Shin et al.
			6,972,080 B1	12/2005	Tomioka et al.

(56)

## References Cited

## U.S. PATENT DOCUMENTS

6,973,706	B2	12/2005	Say et al.	2002/0128546	A1	9/2002	Silver
7,003,336	B2	2/2006	Holker et al.	2002/0151796	A1	10/2002	Koulik
7,003,341	B2	2/2006	Say et al.	2002/0161288	A1	10/2002	Shin et al.
7,008,979	B2	3/2006	Schottman et al.	2002/0169369	A1	11/2002	Ward et al.
7,014,948	B2	3/2006	Lee et al.	2002/0177763	A1	11/2002	Burns et al.
7,033,322	B2	4/2006	Silver	2002/0182241	A1	12/2002	Boerenstein et al.
7,052,131	B2	5/2006	McCabe et al.	2002/0185384	A1	12/2002	Leong et al.
7,058,437	B2	6/2006	Buse et al.	2002/0188185	A1	12/2002	Sohrab
7,060,059	B2	6/2006	Keith et al.	2002/0193885	A1	12/2002	Legeay et al.
7,070,580	B2	7/2006	Nielsen	2003/0004457	A1	1/2003	Andersson
7,074,307	B2	7/2006	Simpson et al.	2003/0006669	A1	1/2003	Pei et al.
7,078,582	B2	7/2006	Stebbins et al.	2003/0009093	A1	1/2003	Silver
7,081,195	B2	7/2006	Simpson et al.	2003/0023317	A1	1/2003	Brauker et al.
7,098,803	B2	8/2006	Mann et al.	2003/0032874	A1	2/2003	Rhodes et al.
7,108,778	B2	9/2006	Simpson et al.	2003/0036773	A1	2/2003	Whitehurst et al.
7,110,803	B2	9/2006	Shults et al.	2003/0036803	A1	2/2003	McGhan et al.
7,115,884	B1	10/2006	Walt et al.	2003/0059631	A1	3/2003	Al-Lamee
7,118,667	B2	10/2006	Lee	2003/0065254	A1	4/2003	Schulman et al.
7,120,483	B2	10/2006	Russell et al.	2003/0069383	A1	4/2003	Van Antwerp et al.
7,134,999	B2	11/2006	Brauker et al.	2003/0070548	A1	4/2003	Clausen
7,136,689	B2	11/2006	Shults et al.	2003/0076082	A1	4/2003	Morgan et al.
7,153,265	B2	12/2006	Vachon	2003/0078481	A1	4/2003	McIvor et al.
7,166,074	B2	1/2007	Reghabit et al.	2003/0078560	A1	4/2003	Miller et al.
7,169,289	B2	1/2007	Schulein et al.	2003/0088166	A1	5/2003	Say et al.
7,172,075	B1	2/2007	Ji	2003/0091433	A1	5/2003	Tam et al.
7,190,988	B2	3/2007	Say et al.	2003/0096424	A1	5/2003	Mao et al.
7,192,450	B2	3/2007	Brauker et al.	2003/0097082	A1	5/2003	Purdy et al.
7,207,974	B2	4/2007	Safabash et al.	2003/0100040	A1	5/2003	Bonnetaze et al.
7,225,535	B2	6/2007	Feldman et al.	2003/0104273	A1	6/2003	Lee et al.
7,226,978	B2	6/2007	Tapsak et al.	2003/0125498	A1	7/2003	McCabe et al.
7,229,471	B2	6/2007	Gale et al.	2003/0125613	A1	7/2003	Enegren et al.
7,241,586	B2	7/2007	Gulati	2003/0130616	A1	7/2003	Steil et al.
7,248,906	B2	7/2007	Dirac et al.	2003/0132227	A1	7/2003	Geisler
7,267,665	B2	9/2007	Steil et al.	2003/0134100	A1	7/2003	Mao et al.
7,279,174	B2	10/2007	Pacetti et al.	2003/0134347	A1	7/2003	Heller et al.
7,310,544	B2	12/2007	Brister et al.	2003/0138674	A1	7/2003	Zeikus et al.
7,335,286	B2	2/2008	Abel et al.	2003/0157409	A1	8/2003	Huang et al.
7,336,984	B2	2/2008	Gough et al.	2003/0181794	A1	9/2003	Rini et al.
7,344,499	B1	3/2008	Prausnitz et al.	2003/0187338	A1	10/2003	Say et al.
7,357,793	B2	4/2008	Pacetti	2003/0188427	A1	10/2003	Say et al.
7,366,556	B2	4/2008	Brister et al.	2003/0199744	A1	10/2003	Buse et al.
7,379,765	B2	5/2008	Petisce et al.	2003/0199745	A1	10/2003	Burson et al.
7,381,184	B2	6/2008	Funderburk et al.	2003/0199878	A1	10/2003	Pohjonen
7,399,277	B2	7/2008	Saidara et al.	2003/0203498	A1	10/2003	Neel et al.
7,417,164	B2	8/2008	Suri	2003/0203991	A1	10/2003	Schottman et al.
7,423,074	B2	9/2008	Lai et al.	2003/0211050	A1	11/2003	Majeti et al.
7,424,318	B2	9/2008	Brister et al.	2003/0211625	A1	11/2003	Cohan
7,426,408	B2	9/2008	DeNuzzio et al.	2003/0217966	A1	11/2003	Tapsak et al.
7,460,898	B2	12/2008	Brister et al.	2003/0225324	A1	12/2003	Anderson et al.
7,467,003	B2	12/2008	Brister et al.	2003/0225361	A1	12/2003	Sabra
7,470,488	B2	12/2008	Lee et al.	2003/0225367	A1	12/2003	Sabra
7,471,972	B2	12/2008	Rhodes et al.	2003/0225437	A1	12/2003	Ferguson
7,494,465	B2	2/2009	Brister et al.	2003/0228681	A1	12/2003	Ritts et al.
7,497,827	B2	3/2009	Brister et al.	2003/0235817	A1	12/2003	Bartkowiak et al.
7,687,586	B2	3/2010	Ward et al.	2004/0006263	A1	1/2004	Anderson et al.
7,771,352	B2	8/2010	Shults et al.	2004/0010207	A1	1/2004	Flaherty et al.
7,881,763	B2	2/2011	Brauker et al.	2004/0011671	A1	1/2004	Shults et al.
7,899,511	B2	3/2011	Shults et al.	2004/0015063	A1	1/2004	DeNuzzio et al.
7,901,354	B2	3/2011	Shults et al.	2004/0015134	A1	1/2004	Lavi et al.
8,050,731	B2	11/2011	Tapsak et al.	2004/0018486	A1	1/2004	Dunn et al.
8,053,018	B2	11/2011	Tapsak et al.	2004/0030285	A1	2/2004	Lavi et al.
8,509,871	B2	8/2013	Rhodes et al.	2004/0030294	A1	2/2004	Mahurkar
2002/0016535	A1	2/2002	Martin et al.	2004/0039406	A1	2/2004	Jessen
2002/0018843	A1	2/2002	Van Antwerp et al.	2004/0045879	A1	3/2004	Shults et al.
2002/0022883	A1	2/2002	Burg	2004/0063167	A1	4/2004	Kaastrop et al.
2002/0023852	A1	2/2002	McIvor et al.	2004/0068230	A1	4/2004	Estes et al.
2002/0025580	A1	2/2002	Vadgama et al.	2004/0074785	A1	4/2004	Holker
2002/0042090	A1	4/2002	Heller et al.	2004/0077075	A1	4/2004	Jensen et al.
2002/0042561	A1	4/2002	Schulman et al.	2004/0078219	A1	4/2004	Kaylor
2002/0055673	A1	5/2002	Van Antwerp et al.	2004/0084306	A1	5/2004	Shin et al.
2002/0084196	A1	7/2002	Liamos et al.	2004/0106741	A1	6/2004	Kriesel et al.
2002/0099997	A1	7/2002	Piret	2004/0106857	A1	6/2004	Gough
2002/0119711	A1	8/2002	Van Antwerp et al.	2004/0111017	A1	6/2004	Say et al.
2002/0120186	A1	8/2002	Keimel et al.	2004/0111144	A1	6/2004	Lawin et al.
2002/0123087	A1	9/2002	Vachon et al.	2004/0120848	A1	6/2004	Teodorczyk
				2004/0133131	A1	7/2004	Kuhn et al.
				2004/0133164	A1	7/2004	Funderburk et al.
				2004/0138543	A1	7/2004	Russell et al.
				2004/0143173	A1	7/2004	Reghabi et al.

(56)

## References Cited

## U.S. PATENT DOCUMENTS

2004/0146909	A1	7/2004	Duong et al.	2005/0282997	A1	12/2005	Ward
2004/0158138	A1	8/2004	Kilcoyne et al.	2006/0003398	A1	1/2006	Heller et al.
2004/0167801	A1	8/2004	Say et al.	2006/0007391	A1	1/2006	McCabe et al.
2004/0173472	A1	9/2004	Jung et al.	2006/0008370	A1	1/2006	Massaro et al.
2004/0176672	A1	9/2004	Silver et al.	2006/0015020	A1	1/2006	Neale et al.
2004/0180391	A1	9/2004	Gratzl et al.	2006/0015024	A1	1/2006	Brister et al.
2004/0186362	A1	9/2004	Brauker et al.	2006/0016700	A1	1/2006	Brister et al.
2004/0186365	A1	9/2004	Jin et al.	2006/0019327	A1	1/2006	Brister et al.
2004/0199059	A1	10/2004	Brauker et al.	2006/0020186	A1	1/2006	Brister et al.
2004/0204687	A1	10/2004	Morgensen	2006/0020191	A1	1/2006	Brister et al.
2004/0213985	A1	10/2004	Lee et al.	2006/0020192	A1	1/2006	Brister et al.
2004/0219664	A1	11/2004	Heller et al.	2006/0036139	A1	2/2006	Brister et al.
2004/0224001	A1	11/2004	Pacetti et al.	2006/0036140	A1	2/2006	Brister et al.
2004/0228902	A1	11/2004	Benz	2006/0036141	A1	2/2006	Kamath et al.
2004/0234575	A1	11/2004	Horres et al.	2006/0036142	A1	2/2006	Brister et al.
2004/0236200	A1	11/2004	Say et al.	2006/0036143	A1	2/2006	Brister et al.
2004/0236251	A1	11/2004	Roe et al.	2006/0036144	A1	2/2006	Brister et al.
2004/0242982	A1	12/2004	Sakata et al.	2006/0047095	A1	3/2006	Pacetti
2004/0254433	A1	12/2004	Bandis et al.	2006/0058868	A1	3/2006	Gale et al.
2005/0006122	A1	1/2005	Burnette	2006/0065527	A1	3/2006	Samproni
2005/0013842	A1	1/2005	Qiu et al.	2006/0067908	A1	3/2006	Ding
2005/0027182	A1	2/2005	Siddiqui et al.	2006/0068208	A1	3/2006	Tapsak et al.
2005/0031689	A1	2/2005	Shults et al.	2006/0078908	A1	4/2006	Pitner et al.
2005/0032246	A1	2/2005	Brennan et al.	2006/0079740	A1	4/2006	Silver et al.
2005/0033132	A1	2/2005	Shults et al.	2006/0086624	A1	4/2006	Tapsak et al.
2005/0038332	A1	2/2005	Saidara et al.	2006/0134165	A1	6/2006	Pacetti
2005/0044088	A1	2/2005	Lindsay et al.	2006/0142524	A1	6/2006	Lai et al.
2005/0051427	A1	3/2005	Brauker et al.	2006/0142525	A1	6/2006	Lai et al.
2005/0054909	A1	3/2005	Petisce et al.	2006/0142526	A1	6/2006	Lai et al.
2005/0056551	A1	3/2005	White et al.	2006/0142651	A1	6/2006	Brister et al.
2005/0056552	A1	3/2005	Simpson et al.	2006/0148985	A1	7/2006	Karthauser
2005/0070770	A1	3/2005	Dirac et al.	2006/0155180	A1	7/2006	Brister et al.
2005/0077584	A1	4/2005	Uhland et al.	2006/0159718	A1	7/2006	Rathenow et al.
2005/0079200	A1	4/2005	Rathenow et al.	2006/0171980	A1	8/2006	Helmus et al.
2005/0090607	A1	4/2005	Tapsak et al.	2006/0173444	A1	8/2006	Choy et al.
2005/0096519	A1	5/2005	DeNuzzio et al.	2006/0177379	A1	8/2006	Asgari
2005/0107677	A1	5/2005	Ward et al.	2006/0183178	A1	8/2006	Gulati
2005/0112169	A1	5/2005	Brauker et al.	2006/0183871	A1	8/2006	Ward et al.
2005/0112172	A1	5/2005	Pacetti	2006/0183984	A1	8/2006	Dobbles et al.
2005/0112358	A1	5/2005	Potyrailo et al.	2006/0183985	A1	8/2006	Brister et al.
2005/0118344	A1	6/2005	Pacetti	2006/0189856	A1	8/2006	Petisce et al.
2005/0119720	A1	6/2005	Gale et al.	2006/0195029	A1	8/2006	Shults et al.
2005/0121322	A1	6/2005	Say	2006/0198864	A1	9/2006	Shults et al.
2005/0124873	A1	6/2005	Shults et al.	2006/0200019	A1	9/2006	Petisce et al.
2005/0133368	A1	6/2005	Davies et al.	2006/0200020	A1	9/2006	Brister et al.
2005/0139489	A1	6/2005	Davies et al.	2006/0200022	A1	9/2006	Brauker et al.
2005/0143635	A1	6/2005	Kamath et al.	2006/0200970	A1	9/2006	Brister et al.
2005/0143675	A1	6/2005	Neel et al.	2006/0204536	A1	9/2006	Shults et al.
2005/0154272	A1	7/2005	Dirac et al.	2006/0211921	A1	9/2006	Brauker et al.
2005/0173245	A1	8/2005	Feldman et al.	2006/0222566	A1	10/2006	Brauker et al.
2005/0176136	A1	8/2005	Burd et al.	2006/0224108	A1	10/2006	Brauker et al.
2005/0176678	A1	8/2005	Horres et al.	2006/0229512	A1	10/2006	Petisce et al.
2005/0177036	A1	8/2005	Shults et al.	2006/0235285	A1	10/2006	Brister et al.
2005/0181012	A1	8/2005	Saint et al.	2006/0249381	A1	11/2006	Petisce et al.
2005/0182451	A1	8/2005	Griffin et al.	2006/0249446	A1	11/2006	Yeager
2005/0183954	A1	8/2005	Hitchcock et al.	2006/0249447	A1	11/2006	Yeager
2005/0184641	A1	8/2005	Armitage et al.	2006/0252027	A1	11/2006	Petisce et al.
2005/0192557	A1	9/2005	Brauker et al.	2006/0253012	A1	11/2006	Petisce et al.
2005/0195930	A1	9/2005	Spital et al.	2006/0258761	A1	11/2006	Boock et al.
2005/0196747	A1	9/2005	Stiene	2006/0258929	A1	11/2006	Goode et al.
2005/0197554	A1	9/2005	Polcha	2006/0263673	A1	11/2006	Kim et al.
2005/0209665	A1	9/2005	Hunter et al.	2006/0263839	A1	11/2006	Ward et al.
2005/0211571	A1	9/2005	Schulein et al.	2006/0269586	A1	11/2006	Pacetti
2005/0215871	A1	9/2005	Feldman et al.	2006/0270922	A1	11/2006	Brauker et al.
2005/0233407	A1	10/2005	Pamidi et al.	2006/0270923	A1	11/2006	Brauker et al.
2005/0239154	A1	10/2005	Feldman et al.	2006/0275857	A1	12/2006	Kjaer et al.
2005/0242479	A1	11/2005	Petisce et al.	2006/0275859	A1	12/2006	Kjaer
2005/0245795	A1	11/2005	Goode et al.	2006/0289307	A1	12/2006	Yu et al.
2005/0245799	A1	11/2005	Brauker et al.	2006/0293487	A1	12/2006	Gaymans et al.
2005/0258037	A1	11/2005	Hajizadeh et al.	2007/0003588	A1	1/2007	Chinn et al.
2005/0261563	A1	11/2005	Zhou et al.	2007/0007133	A1	1/2007	Mang et al.
2005/0266582	A1	12/2005	Modlin et al.	2007/0017805	A1	1/2007	Hodges et al.
2005/0271546	A1	12/2005	Gerber et al.	2007/0032718	A1	2/2007	Shults et al.
2005/0272989	A1	12/2005	Shah et al.	2007/0038044	A1	2/2007	Dobbles et al.
2005/0274665	A1	12/2005	Heilmann et al.	2007/0045902	A1	3/2007	Brauker et al.
				2007/0059196	A1	3/2007	Brister et al.
				2007/0123963	A1	5/2007	Krulevitch
				2007/0129524	A1	6/2007	Sunkara
				2007/0135698	A1	6/2007	Shah et al.

(56)

## References Cited

## U.S. PATENT DOCUMENTS

2007/0142584	A1	6/2007	Schorzman et al.	2009/0062633	A1	3/2009	Brauker et al.
2007/0155851	A1	7/2007	Alli et al.	2009/0076356	A1	3/2009	Simpson
2007/0161769	A1	7/2007	Schorzman et al.	2009/0076360	A1	3/2009	Brister et al.
2007/0163880	A1	7/2007	Woo et al.	2009/0081803	A1	3/2009	Gamsey et al.
2007/0166343	A1	7/2007	Goerne et al.	2009/0099434	A1	4/2009	Liu et al.
2007/0166364	A1	7/2007	Beier et al.	2009/0099436	A1	4/2009	Brister et al.
2007/0173709	A1	7/2007	Petisce et al.	2009/0124879	A1	5/2009	Brister et al.
2007/0173710	A1	7/2007	Petisce et al.	2009/0143660	A1	6/2009	Brister et al.
2007/0173711	A1	7/2007	Shah et al.	2009/0177143	A1	7/2009	Markle et al.
2007/0197889	A1	8/2007	Brister et al.	2009/0182217	A1	7/2009	Li et al.
2007/0197890	A1	8/2007	Boock et al.	2009/0192751	A1	7/2009	Kamath et al.
2007/0200254	A1	8/2007	Curry	2009/0242399	A1	10/2009	Kamath et al.
2007/0200267	A1	8/2007	Tsai	2009/0242425	A1	10/2009	Kamath et al.
2007/0202562	A1	8/2007	Curry	2009/0247855	A1	10/2009	Boock et al.
2007/0202672	A1	8/2007	Curry	2009/0247856	A1	10/2009	Boock et al.
2007/0203568	A1	8/2007	Gale et al.	2009/0264719	A1	10/2009	Markle et al.
2007/0203966	A1	8/2007	Brauker et al.	2011/0124992	A1	5/2011	Brauker et al.
2007/0208246	A1	9/2007	Brauker et al.	2011/0144465	A1	6/2011	Shults et al.
2007/0213611	A1	9/2007	Simpson et al.	2011/0147300	A1	6/2011	Xiao et al.
2007/0215491	A1	9/2007	Heller et al.	2011/0253533	A1	10/2011	Shults et al.
2007/0218097	A1	9/2007	Heller et al.				
2007/0227907	A1	10/2007	Shah et al.				
2007/0229757	A1	10/2007	McCabe et al.				
2007/0232879	A1	10/2007	Brister et al.				
2007/0233013	A1	10/2007	Schoenberg				
2007/0235331	A1	10/2007	Simpson et al.				
2007/0242215	A1	10/2007	Schorzman et al.				
2007/0244379	A1	10/2007	Boock et al.				
2007/0259217	A1	11/2007	Logan				
2007/0275193	A1	11/2007	DeSimone et al.				
2007/0299385	A1	12/2007	Santini et al.				
2007/0299409	A1	12/2007	Whibourne et al.				
2008/0001318	A1	1/2008	Schorzman et al.				
2008/0021008	A1	1/2008	Pacetti et al.				
2008/0021666	A1	1/2008	Goode et al.				
2008/0027301	A1	1/2008	Ward et al.				
2008/0031918	A1	2/2008	Lawin et al.				
2008/0033269	A1	2/2008	Zhang				
2008/0034972	A1	2/2008	Gough et al.				
2008/0038307	A1	2/2008	Hoffmann				
2008/0045824	A1	2/2008	Tapsak et al.				
2008/0071027	A1	3/2008	Pacetti				
2008/0076897	A1	3/2008	Kunzler et al.				
2008/0081184	A1	4/2008	Kubo et al.				
2008/0113207	A1	5/2008	Pacetti et al.				
2008/0138497	A1	6/2008	Pacetti et al.				
2008/0138498	A1	6/2008	Pacetti et al.				
2008/0143014	A1	6/2008	Tang				
2008/0154101	A1	6/2008	Jain et al.				
2008/0187655	A1	8/2008	Markle et al.				
2008/0188722	A1	8/2008	Markle et al.				
2008/0188725	A1	8/2008	Markle et al.				
2008/0188731	A1	8/2008	Brister et al.				
2008/0194935	A1	8/2008	Brister et al.				
2008/0194938	A1	8/2008	Brister et al.				
2008/0208025	A1	8/2008	Shults et al.				
2008/0213460	A1	9/2008	Benter et al.				
2008/0214915	A1	9/2008	Brister et al.				
2008/0214918	A1	9/2008	Brister et al.				
2008/0242961	A1	10/2008	Brister et al.				
2008/0262334	A1	10/2008	Dunn et al.				
2008/0275313	A1	11/2008	Brister et al.				
2008/0296155	A1	12/2008	Shults et al.				
2008/0305009	A1	12/2008	Gamsey et al.				
2008/0305506	A1	12/2008	Suri				
2008/0306368	A1	12/2008	Goode et al.				
2008/0312397	A1	12/2008	Lai et al.				
2009/0004243	A1	1/2009	Pacetti et al.				
2009/0012205	A1	1/2009	Nakada et al.				
2009/0012379	A1	1/2009	Goode et al.				
2009/0018418	A1	1/2009	Markle et al.				
2009/0018426	A1	1/2009	Markle et al.				
2009/0030294	A1	1/2009	Petisce et al.				
2009/0045055	A1	2/2009	Rhodes et al.				
2009/0061528	A1	3/2009	Suri				

## FOREIGN PATENT DOCUMENTS

EP	0 127 958	12/1984
EP	0 284 518	9/1988
EP	0 286 118	10/1988
EP	0 291 130	11/1988
EP	0 313 951	5/1989
EP	0 320 109	6/1989
EP	0 353 328	2/1990
EP	0 362 145	4/1990
EP	0 390 390	10/1990
EP	0 396 788	11/1990
EP	0 476 980	3/1992
EP	0 534 074	3/1993
EP	0 535 898	4/1993
EP	0 539 625	5/1993
EP	0 563 795	10/1993
EP	0 647 849	4/1995
EP	0 776 628	6/1997
EP	0 817 809	1/1998
EP	0 838 230	4/1998
EP	0 862 648	9/1998
EP	0 885 932	12/1998
EP	0 967 788	12/1999
EP	0 995 805	4/2000
EP	1 804 650	7/2007
FR	2656423	6/1991
FR	2760962	9/1998
GB	1 442 303	7/1976
GB	2149918	6/1985
GB	2209836	5/1989
JP	57156004	9/1982
JP	57156005	9/1982
JP	58163402	9/1983
JP	58163403	9/1983
JP	59029693	2/1984
JP	59049803	3/1984
JP	59049805	3/1984
JP	59059221	4/1984
JP	59087004	5/1984
JP	59-211459	11/1984
JP	59209608	11/1984
JP	59209609	11/1984
JP	59209610	11/1984
JP	60245623	12/1985
JP	61238319	10/1986
JP	62074406	4/1987
JP	62083649	4/1987
JP	62083849	4/1987
JP	62102815	5/1987
JP	62227423	10/1987
JP	63130661	6/1988
JP	01018404	1/1989
JP	01018405	1/1989
JP	02002913	1/1990
JP	3-293556	12/1991
JP	05279447	10/1993
JP	8196626	8/1996



(56)

## References Cited

## FOREIGN PATENT DOCUMENTS

JP	2002-189015	7/2002
WO	WO 89/02720	4/1989
WO	WO 90/00738	1/1990
WO	WO 90/07575	7/1990
WO	WO 91/09302	6/1991
WO	WO 92/07525	5/1992
WO	WO 92/13271	8/1992
WO	WO 93/14185	7/1993
WO	WO 93/14693	8/1993
WO	WO 93/19701	10/1993
WO	WO 93/23744	11/1993
WO	WO 94/08236	4/1994
WO	WO 94/22367	10/1994
WO	WO 96/25089	2/1995
WO	WO 95/07109	3/1995
WO	WO 96/01611	1/1996
WO	WO 96/14026	5/1996
WO	WO 96/30431	10/1996
WO	WO 96/32076	10/1996
WO	WO 96/36296	11/1996
WO	WO 97/01986	1/1997
WO	WO 97/06727	2/1997
WO	WO 97/11067	3/1997
WO	WO 97/43633	11/1997
WO	WO 98/19159	5/1998
WO	WO 98/24358	6/1998
WO	WO 98/38906	9/1998
WO	WO 99/56613	4/1999
WO	WO 00/13003	3/2000
WO	WO 00/19887	4/2000
WO	WO 00/32098	6/2000
WO	WO 00/33065	6/2000
WO	WO 00/49940	8/2000
WO	WO 00/59373	10/2000
WO	WO 00/74753	12/2000
WO	WO 01/12158	2/2001
WO	WO 01/20019	3/2001
WO	WO 01/20334	3/2001
WO	WO 01/43660	6/2001
WO	WO 01/58348	8/2001
WO	WO 01/68901	9/2001
WO	WO 01/69222	9/2001
WO	WO 01/88524	11/2001
WO	WO 01/88534	11/2001
WO	WO 02/053764	7/2002
WO	WO 02/058537	8/2002
WO	WO 03/063700	8/2003
WO	WO 03/082091	9/2003
WO	WO 03/101862	12/2003
WO	WO 2005/045394	5/2005
WO	WO 2005/026689	10/2005
WO	WO 2006/017358	2/2006
WO	WO 2006/018425	2/2006
WO	WO 2006/105146	10/2006
WO	WO 2007/114943	10/2007

## OTHER PUBLICATIONS

Kerner, W. (2001): Implantable glucose sensors: present status and future developments. *Exp. Clin. Endocrinol. Diabetes* 109(Suppl 2):S341-346 (2001).

Worsley et al. (2008): Measurement of glucose in blood with a phenylboronic acid optical sensor. *J. Diab. Sci. Tech.* 2(2):213-220 (Mar. 2008).

Wright et al. (1999): Bioelectrochemical dehalogenations via direct electrochemistry of poly(ethylene oxide)-modified myoglobin, *Electrochemistry Comm* 1:603-611 (1999).

Yamasaki et al. (1989): Direct measurement of whole blood glucose by a needle-type sensor. *Clinica Chimica Acta* 93:93-98 (1989).

Yamasaki, Yoshimitsu (1984): The development of a needle-type glucose sensor for wearable artificial endocrine pancreas. *Med. J. Osaka University* 35(1-2):35-34 (1984).

Yang et al. (2004): A comparison of physical properties and fuel cell performance of Nafion and zirconium phosphate / Nafion composite membranes. *J. Membrane Sci* 237:145-161.

Ye et al. (1993): High current density wire quinoprotein glucose dehydrogenase electrode. *Anal. Chem.* 65:238-241 (1993)

Zamzow et al. (1990): Development and evaluation of a wearable blood monitor. *ASAIO Transactions* 36:M588-M591 (1990).

Zethelius et al. (2008): Use of multiple biomarkers to improve the prediction of death from cardiovascular causes. *NEJM* 358:2107-2116 (2008).

Zhang et al. (1994): Elimination of the acetaminophen interference in an implantable glucose sensor. *Anal. Chem.* 66(7):1183-1188 (1994).

Zhu et al. (2002): Planar amperometric glucose sensor based on glucose oxidase immobilized by chitosan film on prussian blue layer. *Sensors* 2:127-136 (2002).

US 7,530,950, 05/12/2009, Brister et al. (withdrawn).

Aalders et al. 1991. Development of a wearable glucose sensor; studies in healthy volunteers and in diabetic patients. *The International Journal of Artificial Organs* 14(2):102-108.

Abe et al. 1992. Characterization of glucose microsensors for intracellular measurements. *Anal. Chem.* 64(18):2160-2163.

Abel et al. 1984. Experience with an implantable glucose sensor as a prerequisite of an artificial beta cell, *Biomed. Biochim. Acta* 43(5):577-584.

Abel et al. 2002. Biosensors for in vivo glucose measurement: can we cross the experimental stage. *Biosens Bioelectron* 17:1059-1070.

Alcock & Turner. 1994. Continuous Analyte Monitoring to Aid Clinical Practice. *IEEE Engineering in Med. & Biol. Mag.* 13:319-325.

American Heritage Dictionary, 4th Edition. 2000. Houghton Mifflin Company, p. 82.

Amin et al. 2003. Hypoglycemia prevalence in prepubertal children with type 1 diabetes on standard insulin regimen: Use of continuous glucose monitoring system. *Diabetes Care* 26(3):662-667.

Answers.com. "xenogenic." *The American Heritage Stedman's Medical Dictionary*. Houghton Mifflin Company, 2002. Answers.com Nov. 7, 2006 <http://www.answers.com/topic/xenogenic>.

Armour et al. Dec. 1990. Application of Chronic Intravascular Blood Glucose Sensor in Dogs. *Diabetes* 39:1519-1526.

Atanasov et al. 1994. Biosensor for continuous glucose monitoring. *Biotechnology and Bioengineering* 43:262-266.

Atanasov et al. 1997. Implantation of a refillable glucose monitoring-telemetry device. *Biosens Bioelectron* 12:669-680.

Aussedat et al. 1997. A user-friendly method for calibrating a subcutaneous glucose sensor-based hypoglycaemic alarm. *Biosensors & Bioelectronics* 12(11):1061-1071.

Bailey et al. 2007. Reduction in hemoglobin A1c with real-time continuous glucose monitoring: results from a 12-week observational study. *Diabetes Technology & Therapeutics* 9(3):203-210.

Baker et al. 1993. Dynamic concentration challenges for biosensor characterization. *Biosensors & Bioelectronics* 8:433-441.

Bani Amer, M. M. 2002. An accurate amperometric glucose sensor based glucometer with eliminated cross-sensitivity. *J Med Eng Technol* 26(5):208-213.

Bard et al. 1980. *Electrochemical Methods*. John Wiley & Sons, pp. 173-175.

Beach et al. 1999. Subminiature implantable potentiostat and modified commercial telemetry device for remote glucose monitoring. *IEEE Transactions on Instrumentation and Measurement* 48(6):1239-1245.

Bellucci et al. Jan. 1986. Electrochemical behaviour of graphite-epoxy composite materials (GECM) in aqueous salt solutions, *Journal of Applied Electrochemistry*, 16(1):15-22.

Bessman et al., Progress toward a glucose sensor for the artificial pancreas, *Proceedings of a Workshop on Ion-Selective Microelectrodes*, Jun. 4-5, 1973, Boston, MA, 189-197.

Biermann et al. 2008. How would patients behave if they were continually informed of their blood glucose levels? A simulation study using a "virtual" patient. *Diab. Technol. & Therapeut.*, 10:178-187.

Bindra et al. 1989. Pulsed amperometric detection of glucose in biological fluids at a surface-modified gold electrode. *Anal Chem* 61:2566-2570.

(56)

## References Cited

## OTHER PUBLICATIONS

- Bindra et al. 1991. Design and In Vitro Studies of a Needle-Type Glucose Senso for Subcutaneous Monitoring. *Anal. Chem* 63:1692-96.
- Bisenberger et al. 1995. A triple-step potential waveform at enzyme multisensors with thick-film gold electrodes for detection of glucose and sucrose. *Sensors and Actuators, B* 28:181-189.
- Bland et al. 1990. A note on the use of the intraclass correlation coefficient in the evaluation of agreement between two methods of measurement. *Comput. Biol. Med.* 20(5):337-340.
- Bobbioni-Harsch et al. 1993. Lifespan of subcutaneous glucose sensors and their performances during dynamic glycaemia changes in rats. *J. Biomed. Eng.* 15:457-463.
- Bode et al. 1999. Continuous glucose monitoring used to adjust diabetes therapy improves glycosylated hemoglobin: A pilot study. *Diabetes Research and Clinical Practice* 46:183-190.
- Bode et al. 2000. Using the continuous glucose monitoring system to improve the management of type 1 diabetes. *Diabetes Technology & Therapeutics*, 2(Suppl 1):S43-48.
- Bode, B. W. 2000. Clinical utility of the continuous glucose monitoring system. *Diabetes Technol Ther*, 2(Suppl 1):S35-41.
- Boedeker Plastics, Inc. 2009. Polyethylene Specifications Data Sheet, [http://www.boedeker.com/polye\\_p.htm](http://www.boedeker.com/polye_p.htm) [Aug. 19, 2009 3:36:33 PM].
- Boland et al. 2001. Limitations of conventional methods of self-monitoring of blood glucose. *Diabetes Care* 24(11):1858-1862.
- Bott, A. W. 1997. A Comparison of Cyclic Voltammetry and Cyclic Staircase Voltammetry Current Separations 16:1, 23-26.
- Bowman, L.; Meindl, J. D. 1986. The packaging of implantable integrated sensors. *IEEE Trans Biomed Eng BME33*(2):248-255.
- Brauker et al. 1995. Neovascularization of synthetic membranes directed by membrane Microarchitecture. *J. Biomed Mater Res* 29:1517-1524.
- Brauker et al. 1998. Sustained expression of high levels of human factor IX from human cells implanted within an immunoisolation device into athymic rodents. *Hum Gene Ther* 9:879-888.
- Brauker et al. 2001. Unraveling Mysteries at the Biointerface: Molecular Mediator of Inhibition of Blood vessel Formation in the Foreign Body Capsule Revealed. *Surfact Biomaterials* 6, 1:5.
- Brauker et al. Jun. 27, 1996. Local Inflammatory Response Around Diffusion Chambers Containing Xenografts Transplantation 61(12):1671-1677.
- Braunwald, 2008. Biomarkers in heart failure. *N. Engl. J. Med.*, 358: 2148-2159.
- Bremer et al. 2001. Benchmark data from the literature for evaluation of new glucose sensing technologies. *Diabetes Technology & Therapeutics* 3(3):409-418.
- Brooks et al. "Development of an on-line glucose sensor for fermentation monitoring." *Biosensors*, 3:45-56 (1987/88).
- Bruckel et al. 1989. In vivo measurement of subcutaneous glucose concentrations with an enzymatic glucose sensor and a wick method. *Klin Wochenschr* 67:491-495.
- Brunner et al. 1998. Validation of home blood glucose meters with respect to clinical and analytical approaches. *Diabetes Care* 21(4):585-590.
- Cai et al. 2004. A wireless, remote query glucose biosensor based on a pH-sensitive polymer. *Anal Chem* 76(4):4038-4043.
- Campanella et al. 1993. Biosensor for direct determination of glucose and lactate in undiluted biological fluids. *Biosensors & Bioelectronics* 8:307-314.
- Candas et al (1994). "An adaptive plasma glucose controller based on a nonlinear insulin/glucose model." *IEEE Transactions on Bio-medical Engineering*, 41(2): 116-124.
- Cass et al. "Ferrocene-mediated enzyme electrodes for amperometric determination of glucose." *Anal. Chem.*, 36:667-71 (1984).
- Cassidy et al., Apr. 1993. Novel electrochemical device for the detection of cholesterol or glucose. *Analyst*, 118:415-418.
- Chase et al. 2001. Continuous subcutaneous glucose monitoring in children with type 1 diabetes. *Pediatrics* 107:222-226.
- Chatterjee et al. 1997. Poly(ether Urethane) and poly(ether urethane urea) membranes with high H<sub>2</sub>S/CH<sub>4</sub> selectivity. *Journal of Membrane Science* 135:99-106.
- Chia et al. 2004. Glucose sensors: toward closed loop insulin delivery. *Endocrinol Metab Clin North Am* 33:175-95.
- Ciba® Irgacure® 2959 Photoinitiator, Product Description. Apr. 2, 1998. Ciba Specialty Chemicals Inc., Basel, Switzerland. 3 pages.
- Claremont et al. 1986. Subcutaneous implantation of a ferrocene-mediated glucose sensor in pigs. *Diabetologia* 29:817-821.
- Claremont et al. Jul. 1986. Potentially-implantable, ferrocene-mediated glucose sensor. *J. Biomed. Eng.* 8:272-274.
- Clark et al. 1987. Configurational cyclic voltammetry: increasing the specificity and reliability of implanted electrodes. *IEEE/Ninth Annual Conference of the Engineering in Medicine and Biology Society*, pp. 0782-0783.
- Clark et al. 1988. Long-term stability of electroenzymatic glucose sensors implanted in mice. *Trans Am Soc Artif Intern Organs* 34:259-265.
- Clark et al., 1981. One-minute electrochemical enzymic assay for cholesterol in biological materials. *Clin. Chem.* 27(12):1978-1982.
- CLSI. Performance metrics for continuous interstitial glucose monitoring; approved guideline, CLSI document POCT05-A. Wayne, PA: Clinical and Laboratory Standards Institute: 2008 28(33), 72 pp.
- Colangelo et al. 1967. Corrosion rate measurements in vivo. *Journal of Biomedical Materials Research*, 1:405-414.
- Colowick et al. 1976. *Methods in Enzymology*, vol. XLIV, Immobilized Enzymes. New York: Academic Press.
- Cox et al. 1985. Accuracy of perceiving blood glucose in IDDM. *Diabetes Care* 8(6):529-536.
- Csoregi et al., 1994. Design, characterization, and one-point in vivo calibration of a subcutaneously implanted glucose electrode. *Anal Chem.* 66(19):3131-3138.
- Danielsson et al. 1988. Enzyme thermistors, *Methods in Enzymology*, 137:181-197.
- D'Arrigo et al. 2003. Porous-Si based bioreactors for glucose monitoring and drugs production. *Proc. of SPIE* 4982:178-184.
- Dassau et al., In silico evaluation platform for artificial pancreatic  $\beta$ -cell development—a dynamic simulator for closed loop control with hardware-in-the-loop, *Diabetes Technology & Therapeutics*, 11(3):1-8, 2009.
- Davies, et al. 1992. Polymer membranes in clinical sensor applications. I. An overview of membrane function, *Biomaterials*, 13(14):971-978.
- Davis et al. 1983. Bioelectrochemical fuel cell and sensor based on a quinoprotein, alcohol dehydrogenase. *Enzyme Microb. Technol.*, vol. 5, September, 383-388.
- Direct 30/30® Blood Glucose Sensor, (Markwell Medical) Catalog, ©1990, ELCO Diagnostics Company. 1 page.
- Dixon et al. 2002. Characterization in vitro and in vivo of the oxygen dependence of an enzyme/polymer biosensor for monitoring brain glucose. *Journal of Neuroscience Methods* 119:135-142.
- DuPont<sup>1</sup> Dimension AR®. 1998. The chemistry analyzer that makes the most of your time, money and effort. Catalog. Dade International, Chemistry Systems. Newark, DE. 18 pages.
- Durliat et al. 1976. Spectrophotometric and electrochemical determinations of L(+)-lactate in blood by use of lactate dehydrogenase from yeast. *Clin. Chem.* 22(11):1802-1805.
- Edwards Lifesciences. Accuracy for your and your patients. Marketing materials, 4 pp. 2002.
- El Deheigy et al. 1986. Optimization of an implantable coated wire glucose sensor. *J. Biomed Eng.* 8: 121-129.
- Electronic File History for U.S. Appl. No. 09/916,711, filed Jul. 27, 2001 (Abandoned) containing Office Action(s) dated Sep. 24, 2003, Feb. 11, 2004, Jul. 23, 2004, Dec. 23, 2004, Jul. 1, 2005, Sep. 23, 2005 and Feb. 14, 2006 and Applicant(s) Response(s) filed Nov. 24, 2003, Apr. 26, 2004, Oct. 18, 2004, Nov. 22, 2004, Mar. 25, 2005, Sep. 7, 2005, Sep. 30, 2005 and Jun. 15, 2006.
- Electronic File History U.S. Appl. No. 11/021,162, filed Dec. 22, 2004 (U.S. Pat. No. 7,471,972, issued Dec. 30, 2008) containing Office Action(s) dated Jun. 19, 2008 and Sep. 24, 2008 and Applicant(s) Response(s) filed Jan. 16, 2007 and Sep. 15, 2008.

(56)

## References Cited

## OTHER PUBLICATIONS

- El-Khatib et al. 2007. Adaptive closed-loop control provides blood-glucose regulation using dual subcutaneous insulin and glucagon infusion in diabetic swine, *Journal of Diabetes Science and Technology*, 1(2):181-192.
- El-Sa'ad et al. 1990. Moisture Absorption by Epoxy Resins: the Reverse Thermal Effect. *Journal of Materials Science* 25:3577-3582.
- Ernst et al. 2002. Reliable glucose monitoring through the use of microsystem technology. *Anal. Bioanal. Chem.* 373:758-761.
- Fahy et al., An analysis: hyperglycemic intensive care patients need continuous glucose monitoring—easier said than done, *Journal of Diabetes Science and Technology*, 2(2):201-204, Mar. 2008.
- Fare et al. 1998. Functional characterization of a conducting polymer-based immunoassay system. *Biosensors & Bioelectronics* 13(3-4):459-470.
- Feldman et al. 2003. A continuous glucose sensor based on wired enzyme technology—results from a 3-day trial in patients with type 1 diabetes. *Diabetes Technol Ther* 5(5):769-779.
- Fischer et al. 1987. Assessment of subcutaneous glucose concentration: validation of the wick technique as a reference for implanted electrochemical sensors in normal and diabetic dogs, *Diabetologia* 30:940-945.
- Fischer et al. 1989. Oxygen Tension at the Subcutaneous Implantation Site of Glucose Sensors. *Biomed. Biochem* 11/12:965-972.
- Fischer et al. 1995. Hypoglycaemia-warning by means of subcutaneous electrochemical glucose sensors: an animal study, *Horm. Metab. Res.* 27:53.
- Freedman et al. 1991. *Statistics*, Second Edition, W.W. Norton & Company, p. 74.
- Frohnauer et al. 2001. Graphical human insulin time-activity profiles using standardized definitions. *Diabetes Technology & Therapeutics* 3(3):419-429.
- Frost et al. 2002. Implantable chemical sensors for real-time clinical monitoring: Progress and challenges. *Current Opinion in Chemical Biology* 6:633-641.
- Gabbay et al. 2008. Optical coherence tomography-based continuous noninvasive glucose monitoring in patients with diabetes. *Diab. Technol. & Therapeut.*, 10:188-193.
- Ganesan et al., Gold layer-based dual crosslinking procedure of glucose oxidase with ferrocene monocarboxylic acid provides a stable biosensor, *Analytical Biochemistry* 343:188-191, 2005.
- Ganesh et al., Evaluation of the VIA® blood chemistry monitor for glucose in healthy and diabetic volunteers, *Journal of Diabetes Science and Technology*, 2(2):182-193, Mar. 2008.
- Gao et al. 1989. Determination of Interfacial parameters of cellulose acetate membrane materials by HPLC, *J. Liquid Chromatography*, VI, 12, n. 11, 2083-2092.
- Garg et al. 2004. Improved Glucose Excursions Using an Implantable Real-Time continuous Glucose Sensor in Adults with Type I Diabetes. *Diabetes Care* 27:734-738.
- Geller et al. 1997. Use of an immunoisolation device for cell transplantation and tumor immunotherapy. *Ann NY Acad Sci* 831:438-451.
- Gerritsen et al. 1999. Performance of subcutaneously implanted glucose sensors for continuous monitoring. *The Netherlands Journal of Medicine* 54:167-179.
- Gerritsen et al. 2001. Influence of inflammatory cells and serum on the performance of implantable glucose sensors. *J Biomed Mater Res* 54:69-75.
- Gerritsen, M. 2000. Problems associated with subcutaneously implanted glucose sensors. *Diabetes Care* 23(2):143-145.
- Gilligan et al. 1994. Evaluation of a subcutaneous glucose sensor out to 3 months in a dog model. *Diabetes Care* 17(8):882-887.
- Gilligan et al. 2004. Feasibility of continuous long-term glucose monitoring from a subcutaneous glucose sensor in humans. *Diabetes Technol Ther* 6:378-386.
- Godsland et al. 2001. Maximizing the Success Rate of Minimal Model Insulin Sensitivity Measurement in Humans: The Importance of Basal Glucose Levels. *The Biochemical Society and the Medical Research Society*, 1-9.
- Gouda et al., Jul. 4, 2003. Thermal inactivation of glucose oxidase, *The Journal of Biological Chemistry*, 278(27):24324-24333.
- Gough et al. 2000. Immobilized glucose oxidase in implantable glucose sensor technology. *Diabetes Technology & Therapeutics* 2(3):377-380.
- Gough et al. 2003. Frequency characterization of blood glucose dynamics. *Annals of Biomedical Engineering* 31:91-97.
- Gross et al. 2000. Efficacy and reliability of the continuous glucose monitoring system. *Diabetes Technology & Therapeutics*, 2(Suppl 1):S19-26.
- Gross et al. 2000. Performance evaluation of the MiniMed® continuous glucose monitoring system during patient home use. *Diabetes Technology & Therapeutics* 2(1):49-56.
- Guerci et al., Clinical performance of CGMS in type 1 diabetic patients treated by continuous subcutaneous insulin infusion using insulin analogs, *Diabetes Care*, 26:582-589, 2003.
- Guo et al., Modification of cellulose acetate ultrafiltration membrane by gamma ray radiation, *Shuichuli Jishi Bianji Weiyuanhui*, 23(6):315-318, 1998 (Abstract only).
- Hall et al. 1998. Electrochemical oxidation of hydrogen peroxide at platinum electrodes. Part I: An adsorption-controlled mechanism. *Electrochimica Acta*, 43(5-6):579-588.
- Hall et al. 1998. Electrochemical oxidation of hydrogen peroxide at platinum electrodes. Part II: Effect of potential. *Electrochimica Acta* 43(14-15):2015-2024.
- Hall et al. 1999. Electrochemical oxidation of hydrogen peroxide at platinum electrodes. Part III: Effect of temperature. *Electrochimica Acta*, 44:2455-2462.
- Hall et al. 1999. Electrochemical oxidation of hydrogen peroxide at platinum electrodes. Part IV: Phosphate buffer dependence. *Electrochimica Acta*, 44:4573-4582.
- Hall et al. 2000. Electrochemical oxidation of hydrogen peroxide at platinum electrodes. Part V: Inhibition by chloride. *Electrochimica Acta*, 45:3573-3579.
- Hamilton Syringe Selection Guide. 2006. Syringe Selection. [www.hamiltoncompany.com](http://www.hamiltoncompany.com).
- Harrison et al. 1988. Characterization of perfluorosulfonic acid polymer coated enzyme electrodes and a miniaturized integrated potentiostat for glucose analysis in whole blood. *Anal. Chem.* 60:2002-2007.
- Hashiguchi et al. (1994). "Development of a miniaturized glucose monitoring system by combining a needle-type glucose sensor with microdialysis sampling method: Long-term subcutaneous tissue glucose monitoring in ambulatory diabetic patients," *Diabetes Care*, 17(5): 387-396.
- Heller, "Electrical wiring of redox enzymes," *Acc. Chem. Res.*, 23:128-134 (1990).
- Heller, A. 1992. Electrical Connection of Enzyme Redox Centers to Electrodes. *J. Phys. Chem.* 96:3579-3587.
- Heller, A. 1999. Implanted electrochemical glucose sensors for the management of diabetes. *Annu Rev Biomed Eng* 1:153-175.
- Heller, A. 2003. Plugging metal connectors into enzymes. *Nat Biotechnol* 21:631-2.
- Hicks, 1985. *In Situ Monitoring*, *Clinical Chemistry*, 31(12):1931-1935.
- Hitchman, M. L. 1978. Measurement of Dissolved Oxygen. In *Elving et al. (Eds.). Chemical Analysis*, vol. 49, Chap. 3, pp. 34-49, 59-123. New York: John Wiley & Sons.
- Hoel, Paul G. 1976. *Elementary Statistics*, Fourth Edition. John Wiley & Sons, Inc., pp. 113-114.
- Hrapovic et al. 2003. Picoamperometric detection of glucose at ultrasmall platinum-based biosensors: preparation and characterization. *Anal Chem* 75:3308-3315.
- <http://www.merriam-webster.com/dictionary>, definition for "aberrant," Aug. 19, 2008, p. 1.
- Hu, et al. 1993. A needle-type enzyme-based lactate sensor for in vivo monitoring, *Analytica Chimica Acta*, 281:503-511.
- Huang et al. Aug. 1975. Electrochemical Generation of Oxygen. 1: The Effects of Anions and Cations on Hydrogen Chemisorption and Anodic Oxide Film Formation on Platinum Electrode. 2: The Effects of Anions and Cations on Oxygen Generation on Platinum Electrode, pp. 1-116.

(56)

## References Cited

## OTHER PUBLICATIONS

- Huang et al., Sep. 1997, A 0.5mW Passive Telemetry IC for Biomedical Applications, Proceedings of the 23rd European Solid-State Circuits Conference (ESSCIRC '97), pp. 172-175, Southampton, UK.
- Hunter et al. Mar. 31, 2000. Minimally Invasive Glucose Sensor and Insulin Delivery System. MIT Home Automation and Healthcare Consortium. Progress Report No. 2-5. 17 pages.
- IPER dated Apr. 18, 2005 for PCT/US02/23903 filed Jul. 26, 2002.
- Ishikawa et al. 1998. Initial evaluation of a 290-mm diameter subcutaneous glucose sensor: Glucose monitoring with a biocompatible, flexible-wire, enzyme-based amperometric microsensor in diabetic and nondiabetic humans. *Journal of Diabetes and Its Complications*, 12:295-301.
- ISR dated Feb. 27, 2003 for PCT/US02/23903 filed Jul. 26, 2002.
- Jaffari et al. 1995. Recent advances in amperometric glucose biosensors for in vivo monitoring, *Physiol. Meas.* 16: 1-15.
- Jensen et al. 1997. Fast wave forms for pulsed electrochemical detection of glucose by incorporation of reductive desorption of oxidation products. *Analytical Chemistry* 69(9):1776-1781.
- Jeutter, D. C. 1982. A transcutaneous implanted battery-recharging and biotelemetry power switching system. *IEEE Trans Biomed Eng* 29:314-321.
- Jobst et al., (1996) Thin-Film Microbiosensors for Glucose-Lactate Monitoring, *Anal. Chem.* 68(18): 3173-3179.
- Johnson (1991). "Reproducible electrodeposition of biomolecules for the fabrication of miniature electroenzymatic biosensors," *Sensors and Actuators B*, 5:85-89.
- Johnson et al. 1992. In vivo evaluation of an electroenzymatic glucose sensor implanted in subcutaneous tissue. *Biosensors & Bioelectronics*, 7:709-714.
- Jovanovic et al. 1997. The Thermogravimetric analysis of some polysiloxanes. *Polym Degrad Stability* 61: 87-93.
- Jovanovic, L. 2000. The role of continuous glucose monitoring in gestational diabetes mellitus. *Diabetes Technology & Therapeutics*, 2 Suppl 1, S67-71.
- Kacaniklic May-Jun. 1994. *Electroanalysis*, 6(5-6):381-390.
- Kamath et al. Calibration of a continuous glucose monitor: effect of glucose rate of change, Eighth Annual Diabetes Technology Meeting, Nov. 13-15 2008, p. A88.
- Kang et al. 2003. In vitro and short-term in vivo characteristics of a Kel-F thin film modified glucose sensor. *Anal. Sci.* 19:1481-1486.
- Kargol et al. 2001. Studies on the structural properties of porous membranes: measurement of linear dimensions of solutes. *Biophys. Chem.* 91:263-271.
- Kaufman et al. 2001. A pilot study of the continuous glucose monitoring system. *Diabetes Care* 24(12):2030-2034.
- Kaufman. 2000. Role of the continuous glucose monitoring system in pediatric patients. *Diabetes Technology & Therapeutics* 2(1):S-49-S-52.
- Kawagoe et al. 1991. Enzyme-modified organic conducting salt microelectrode, *Anal. Chem.* 63:2961-2965.
- Keedy et al. 1991. Determination of urate in undiluted whole blood by enzyme electrode. *Biosensors & Bioelectronics*, 6: 491-499.
- Kerner et al. "The function of a hydrogen peroxide-detecting electroenzymatic glucose electrode is markedly impaired in human sub-cutaneous tissue and plasma," *Biosensors & Bioelectronics*, 8:473-482 (1993).
- Kerner et al. 1988. A potentially implantable enzyme electrode for amperometric measurement of glucose, *Horm. Metab. Res. Suppl.* 20:8-13.
- Kiechle, F.L. 2001. The impact of continuous glucose monitoring on hospital point-of-care testing programs. *Diabetes Technol. Ther.* 3:647-649.
- Klueh et al. 2003. Use of Vascular Endothelial Cell Growth Factor Gene Transfer to Enhance Implantable Sensor Function in Vivo, *Biosensor Function and VEGF-Gene Transfer*, pp. 1072-1086.
- Ko, Wen H. 1985. Implantable Sensors for Closed-Loop Prosthetic Systems, Futura Pub. Co., Inc., Mt. Kisco, NY, Chapter 15:197-210.
- Kondo et al. 1982. A miniature glucose sensor, implantable in the blood stream. *Diabetes Care*. 5(3):218-221.
- Koschinsky et al. 1998. New approach to technical and clinical evaluation of devices for self-monitoring of blood glucose. *Diabetes Care* 11(8): 619-619.
- Koschinsky et al. 2001. Sensors for glucose monitoring: Technical and clinical aspects. *Diabetes Metab. Res. Rev.* 17:113-123.
- Kost et al. 1985. Glucose-sensitive membranes containing glucose oxidase: activity, swelling, and permeability studies, *Journal of Biomedical Materials Research* 19:1117-1133.
- Koudelka et al. 1989. In vivo response of microfabricated glucose sensors to glycemia changes in normal rats. *Biomed. Biochim. Acta* 48(11-12):953-956.
- Koudelka et al. 1991. In-vivo behaviour of hypodermically implanted microfabricated glucose sensors. *Biosensors & Bioelectronics* 6:31-36.
- Kraver et al. 2001. A mixed-signal sensor interface microinstrument. *Sensors and Actuators A* 91:266-277.
- Kruger et al. 2000. Psychological motivation and patient education: A role for continuous glucose monitoring. *Diabetes Technology & Therapeutics*, 2(Suppl 1):S93-97.
- Kulys et al., 1994. Carbon-paste biosensors array for long-term glucose measurement, *Biosensors & Bioelectronics*, 9:491-500.
- Kunjan et al., Automated blood sampling and glucose sensing in critical care settings, *Journal of Diabetes Science and Technology* 2(3):194-200, Mar. 2008.
- Kurtz et al. 2005. Recommendations for blood pressure measurement in humans and experimental animals, Part 2: Blood pressure measurement in experimental animals, A statement for professionals from the subcommittee of professional and public education of the American Heart Association Council on High Blood Pressure Research. *Hypertension* 45:299-310.
- Kusano, H. Glucose enzyme electrode with percutaneous interface which operates independently of dissolved oxygen. *Clin. Phys. Physiol. Meas.* 1989. 10(1): 1-9.
- Ladd et al., Structure Determination by X-ray Crystallography, 3rd ed. Plenum, 1996, Ch. 1, pp. xxi-xxiv and 1-58.
- Lee et al. 1999. Effects of pore size, void volume, and pore connectivity on tissue responses. Society for Biomaterials 25th Annual Meeting, 171.
- Lehmann et al. May 1994. Retrospective validation of a physiological model of glucose-insulin interaction in type 1 diabetes mellitus, *Med. Eng. Phys.* 16:193-202.
- Lerner et al. 1984. An implantable electrochemical glucose sensor. *Ann. N. Y. Acad. Sci.* 428:263-278.
- Lewandowski et al. 1988. Evaluation of a miniature blood glucose sensor. *Trans. Am. Soc. Artif. Intern. Organs* 34:255-258.
- Leybold et al. 1984. Model of a two-substrate enzyme electrode for glucose. *Anal. Chem.* 56:2896-2904.
- Linke et al. 1994. Amperometric biosensor for in vivo glucose sensing based on glucose oxidase immobilized in a redox hydrogel. *Biosensors & Bioelectronics* 9:151-158.
- Lowe, 1984. *Biosensors, Trends in Biotechnology*, 2(3):59-65.
- Luong et al. 2004. Solubilization of Multiwall Carbon Nanotubes by 3-Aminopropyltriethoxysilane Towards the Fabrication of Electrochemical Biosensors with Promoted Electron Transfer. *Electroanalysis* 16(1-2):132-139.
- Lyandres et al. (2008). Progress toward an in vivo surface-enhanced Raman spectroscopy glucose sensor. *Diabetes Technology & Therapeutics*, 10(4): 257-265.
- Lyman D. 1960. Polyurethanes. I. The Solution Polymerization of Diisocyanates with Ethylene Glycol. *J. Polymer Sci.* XLV:45-49.
- Maidan et al. 1992. Elimination of Electrooxidizable Interferent-Produced Currents in Amperometric Biosensors, *Analytical Chemistry*, 64:2889-2896.
- Makale et al. 2003. Tissue window chamber system for validation of implanted oxygen sensors. *Am. J. Physiol. Heart Circ. Physiol.* 284:H2288-2294.
- Malin et al. 1999. Noninvasive Prediction of Glucose by Near-Infrared Diffuse Reflectance Spectroscopy. *Clinical Chemistry* 45:9, 1651-1658.
- Maran et al. 2002. Continuous subcutaneous glucose monitoring in diabetic patients: A multicenter analysis. *Diabetes Care* 25(2):347-352.

(56)

## References Cited

## OTHER PUBLICATIONS

- March, W. F. 2002. Dealing with the delay. *Diabetes Technol Ther* 4(1):49-50.
- Marena et al. 1993. The artificial endocrine pancreas in clinical practice and research. *Panminerva Medica* 35(2):67-74.
- Mascini et al. 1989. Glucose electrochemical probe with extended linearity for whole blood. *J Pharm Biomed Anal* 7(12): 1507-1512.
- Mastrototaro et al. "An electroenzymatic glucose sensor fabricated on a flexible substrate." *Sensors and Actuators B*, 5:139-44 (1991).
- Mastrototaro et al. 2003. Reproducibility of the continuous glucose monitoring system matches previous reports and the intended use of the product. *Diabetes Care* 26:256; author reply p. 257.
- Mastrototaro, J. J. 2000. The MiniMed continuous glucose monitoring system. *Diabetes Technol Ther* 2(Suppl 1):513-8.
- Matsumoto et al. 1998. A micro-planar amperometric glucose sensor unsusceptible to interference species. *Sensors and Actuators B* 49:68-72.
- Matsumoto et al. 2001. A long-term lifetime amperometric glucose sensor with a perfluorocarbon polymer coating. *Biosens Bioelectron* 16:271-276.
- Matthews et al. 1988. An amperometric needle-type glucose sensor testing in rats and man. *Diabetic Medicine* 5:248-252.
- Mazze et al. 2008. Characterizing glucose exposure for individuals with normal glucose tolerance using continuous glucose monitoring and ambulatory glucose profile analysis. *Diab. Technol. & Therapeut.*, 10:149-159.
- McCartney et al. 2001. Near-infrared fluorescence lifetime assay for serum glucose based on allophycocyanin-labeled concanavalin A. *Anal Biochem* 292:216-221.
- McGrath et al. 1995. The use of differential measurements with a glucose biosensor for interference compensation during glucose determinations by flow injection analysis. *Biosens Bioelectron* 10:937-943.
- McKean, et al. Jul. 7, 1988. A Telemetry Instrumentation System for Chronically Implanted Glucose and Oxygen Sensors. *Transactions on Biomedical Engineering* 35:526-532.
- Memoli et al. 2002. A comparison between different immobilised glucoseoxidase-based electrodes. *J Pharm Biomed Anal* 29:1045-1052.
- Merriam-Webster Online Dictionary. Apr. 23, 2007. Definition of "nominal". <http://www.merriam-webster.com/dictionary/nominal>.
- Merriam-Webster Online Dictionary. Definition of "acceleration". <http://www.merriam-webster.com/dictionary/Acceleration> Jan. 11, 2010.
- Merriam-Webster Online Dictionary. Definition of "system". <http://www.merriam-webster.com/dictionary/System> Jan. 11, 2010.
- Meyerhoff et al. 1992. On line continuous monitoring of subcutaneous tissue glucose in men by combining portable glucosensor with microdialysis. *Diabetologia* 35:1087-1092.
- Miller et al. 1989. In vitro stimulation of fibroblast activity by factors generated from human monocytes activated by biomedical polymers. *Journal of J Biomed Mater Res* 23:911-930.
- Miller et al. 1989. Generation of IL1-like activity in response to biomedical polymer implants: a comparison of in vitro and in vivo models. *J Biomed Mater Res* 23:1007-1026.
- Miller, A. 1988. Human monocyte/macrophage activation and interleukin 1 generation by biomedical polymers. *J Biomed Mater Res* 23:713-731.
- Moatti-Sirat et al. 1992. Towards continuous glucose monitoring: in vivo evaluation of a miniaturized glucose sensor implanted for several days in rat subcutaneous tissue. *Diabetologia* 35:224-230.
- Moatti-Sirat et al., Reduction of acetaminophen interference in glucose sensors by a composite Nafion membrane: demonstration in rats and man, *Diabetologia* 37(6):610-616, Jun. 1994.
- Moatti-Sirat, D et al. 1992. Evaluating in vitro and in vivo the interference of ascorbate and acetaminophen on glucose detection by a needle-type glucose sensor. *Biosensors and Bioelectronics* 7:345-352.
- Morff et al. 1990. Microfabrication of reproducible, economical, electroenzymatic glucose sensors, Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 12(2):0483-0484.
- Mosbach et al. 1975. Determination of heat changes in the proximity of immobilized enzymes with an enzyme thermistor and its use for the assay of metabolites, *Biochim. Biophys. Acta. (Enzymology)*, 403:256-265.
- Motonaka et al. 1993. Determination of cholesterol and cholesterol ester with novel enzyme microsenors, *Anal. Chem.* 65:3258-3261.
- Moussy et al. 2000. Biomaterials community examines biosensor biocompatibility *Diabetes Technol Ther* 2:473-477.
- Moussy et al. 1993. Performance of subcutaneously implanted needle-type glucose sensors employing a novel trilayer coating, *Anal Chem.* 65: 2072-2077.
- Moussy, Francis (Nov. 2002) Implantable Glucose Sensor: Progress and Problems, *Sensors*, 1:270-273.
- Mowery et al. 2000. Preparation and characterization of hydrophobic polymeric films that are thromboresistant via nitric oxide release. *Biomaterials* 21:9-21.
- Murphy, et al. 1992. Polymer membranes in clinical sensor applications. II. The design and fabrication of permselective hydrogels for electrochemical devices, *Biomaterials*, 13(14):979-990.
- Muslu. 1991. Trickling filter performance. *Applied Biochemistry and Biotechnology* 37:211-224.
- Myler et al. 2002. Ultra-thin-polysiloxane-film-composite membranes for the optimisation of amperometric oxidase enzyme electrodes. *Biosens Bioelectron* 17:35-43.
- Nafion® 117 Solution Product Description, Product No. 70160, Sigma-Aldrich Corp., St. Louis, Mo. Downloaded from <https://www.sigmaaldrich.com/cgi-bin/hsrun/Suite7/Suite/HAHTpage/Suite>. HsExternal Prod . . . on Apr. 7, 2005.
- Nam et al. 2000. A novel fabrication method of macroporous biodegradable polymer scaffolds using gas foaming salt as a porogen additive. *J Biomed Mater Res* 53:1-7.
- Ohara et al. 1994. "Wired" enzyme electrodes for amperometric determination of glucose or lactate in the presence of interfering substances. *Anal Chem* 66:2451-2457.
- Ohara, et al. Dec. 1993. Glucose electrodes based on cross-linked bis(2,2'-bipyridine)chloroosmium(+2+) complexed poly(1-vinylimidazole) films, *Analytical Chemistry*, 65:3512-3517.
- Okuda et al. 1971. Mutarotase effect on micro determinations of D-glucose and its anomers with  $\beta$ -D-glucose oxidase. *Anal Biochem* 43:312-315.
- Oxford English Dictionary Online. Definition of "impending". <http://www.askoxford.com/results/?view=dev dict&field=12668446> Impending&branch= Jan. 11, 2010.
- Palmisano et al. 2000. Simultaneous monitoring of glucose and lactate by an interference and cross-talk free dual electrode amperometric biosensor based on electropolymerized thin films. *Biosensors & Bioelectronics* 15:531-539.
- Park et al. 2002. Gas separation properties of polysiloxane/polyether mixed soft segment urethane urea membranes, *J. Membrane Science*, 204: 257-269.
- Patel et al. 2003. Amperometric glucose sensors based on ferrocene containing polymeric electron transfer systems—a preliminary report. *Biosens Bioelectron* 18:1073-6.
- Peacock et al. 2008. Cardiac troponin and outcome in acute heart failure. *N. Engl. J. Med.*, 358: 2117-2126.
- Pegoraro et al. 1995. Gas transport properties of siloxane polyurethanes, *Journal of Applied Polymer Science*, 57:421-429.
- Pfeiffer et al. 1992. On line continuous monitoring of subcutaneous tissue glucose is feasible by combining portable glucosensor with microdialysis. *Horm. Metab. Res.* 25:121-124.
- Pfeiffer, E.F. 1990. The glucose sensor: the missing link in diabetes therapy, *Horm Metab Res Suppl.* 24:154-164.
- Phillips and Smith. 1988. Biomedical Applications of Polyurethanes: Implications of Failure Mechanisms. *J. Biomat. Appl.* 3:202-227.
- Pichert et al. 2000. Issues for the coming age of continuous glucose monitoring *Diabetes Educ* 26(6):969-980.
- Pickup et al. "Implantable glucose sensors: choosing the appropriate sensor strategy," *Biosensors*, 3:335-346 (1987/88).

(56)

## References Cited

## OTHER PUBLICATIONS

- Pickup et al. "In vivo molecular sensing in diabetes mellitus: an implantable glucose sensor with direct electron transfer," *Diabetologia*, 32:213-217 (1989).
- Pickup et al. 1989. Potentially-implantable, amperometric glucose sensors with mediated electron transfer: improving the operating stability. *Biosensors* 4:109-119.
- Pickup et al. 1993. Developing glucose sensors for in vivo use. Elsevier Science Publishers Ltd (UK), TIBTECH vol. 11: 285-291.
- Pinner et al., Cross-linking of cellulose acetate by ionizing radiation, *Nature*, vol. 184, 1303-1304, Oct. 24, 1959.
- Pishko et al. "Amperometric glucose microelectrodes prepared through immobilization of glucose oxidase in redox hydrogels," *Anal. Chem.*, 63:2268-72 (1991).
- Pitzer et al. 2001. Detection of hypoglycemia with the GlucoWatch biographer. *Diabetes Care* 24(5):881-885.
- Poitout et al. 1993. A glucose monitoring system for on line estimation in man of blood glucose concentration using a miniaturized glucose sensor implanted in the subcutaneous tissue and a wearable control unit. *Diabetologia* 36:658-663.
- Poitout et al. 1994. Development of a glucose sensor for glucose monitoring in man: the disposable implant concept. *Clinical Materials* 15:241-246.
- Poitout, et al. 1991. In Vitro and In Vivo Evaluation in Dogs of a Miniaturized Glucose Sensor, *ASAIO Transactions*, 37:M298-M300.
- Postlethwaite et al. 1996. Interdigitated array electrode as an alternative to the rotated ring-disk electrode for determination of the reaction products of dioxygen reduction. *Analytical Chemistry* 68:2951-2958.
- Prabhu et al. 1981. Electrochemical studies of hydrogen peroxide at a platinum disc electrode, *Electrochimica Acta* 26(6):725-729.
- Quinn et al. 1995. Kinetics of glucose delivery to subcutaneous tissue in rats measured with 0.3-mm amperometric microsenors. *The American Physiological Society* E155-E161.
- Quinn et al. 1997. Biocompatible, glucose-permeable hydrogel for in situ coating of implantable biosensors. *Biomaterials* 18:1665-1670.
- Rabah et al., 1991. Electrochemical wear of graphite anodes during electrolysis of brine, *Carbon*, 29(2):165-171.
- Ratner, B.D. 2002. Reducing capsular thickness and enhancing angiogenesis around implant drug release systems. *J Control Release* 78:211-218.
- Reach et al. 1986. A Method for Evaluating in vivo the Functional Characteristics of Glucose Sensors. *Biosensors* 2:211-220.
- Reach et al. 1992. Can continuous glucose monitoring be used for the treatment of diabetes? *Analytical Chemistry* 64(5):381-386.
- Reach, G. 2001. Which threshold to detect hypoglycemia? Value of receiver-operator curve analysis to find a compromise between sensitivity and specificity. *Diabetes Care* 24(5):803-804.
- Reach, Gerard. 2001. Letters to the Editor Re: *Diabetes Technology & Therapeutics*, 2000;2:49-56. *Diabetes Technology & Therapeutics* 3(1):129-130.
- Rebrin et al. "Automated feedback control of subcutaneous glucose concentration in diabetic dogs," *Diabetologia*, 32:573-76 (1989).
- Rebrin et al. 1992. Subcutaneous glucose monitoring by means of electrochemical sensors: fiction or reality? *J. Biomed. Eng.* 14:33-40.
- Reusch. 2004. Chemical Reactivity. *Organometallic Compounds*. Virtual Textbook of Organic Chem. pp. 1-16, <http://www.cem.msu.edu/~reusch/VirtualText/orgmetal.htm>.
- Rhodes et al. 1994. Prediction of pocket-portable and implantable glucose enzyme electrode performance from combined species permeability and digital simulation analysis. *Analytical Chemistry* 66(9):1520-1529.
- Rigla et al. 2008. Real-time continuous glucose monitoring together with telemedical assistance improves glycemic control and glucose stability in pump-treated patients. *Diab. Technol. & Therapeut.*, 10:194-199.
- Rivers et al., Central venous oxygen saturation monitoring in the critically ill patient, *Current in Critical Care*, 7:204-211, 2001.
- Sakakida et al. 1992. Development of Ferrocene-Mediated Needle-Type Glucose Sensor as a Measure of True Subcutaneous Tissue Glucose Concentrations. *Artif. Organs Today* 2(2):145-158.
- Sakakida et al. 1993. Ferrocene-Mediated Needle Type Glucose Sensor Covered with Newly Designed Biocompatible Membran, *Sensors and Actuators B* 13-14:319-322.
- Salardi et al. 2002. The glucose area under the profiles obtained with continuous glucose monitoring system relationships with HbA1c in pediatric type 1 diabetic patients. *Diabetes Care* 25(10):1840-1844.
- Samuels, M.P. 2004. The effects of flight and altitude. *Arch Dis Child*. 89: 448-455.
- San Diego Plastics, Inc. 2009. Polyethylene Data Sheet, <http://www.sdplastics.com/polyeth.html>.
- Sansen et al. 1985. "Glucose sensor with telemetry system." In Ko, W. H. (Ed.). *Implantable Sensors for Closed Loop Prosthetic Systems*. Chap. 12, pp. 167-175, Mount Kisco, NY: Futura Publishing Co.
- Sansen et al. 1990. A smart sensor for the voltammetric measurement of oxygen or glucose concentrations. *Sensors and Actuators B* 1:298-302.
- Schmidt et al. 1993. Glucose concentration in subcutaneous extracellular space. *Diabetes Care* 16(5):695-700.
- Schmidtke et al., Measurement and modeling of the transient difference between blood and subcutaneous glucose concentrations in the rat after injection of insulin. *Proc Natl Acad Sci U S A* 1998, 95, 294-299.
- Schoemaker et al. 2003. The SCGM1 system: Subcutaneous continuous glucose monitoring based on microdialysis technique. *Diabetes Technology & Therapeutics* 5(4):599-608.
- Schoonen et al. 1990 Development of a potentially wearable glucose sensor for patients with diabetes mellitus: design and in-vitro evaluation. *Biosensors & Bioelectronics* 5:37-46.
- Schuler et al. 1999. Modified gas-permeable silicone rubber membranes for covalent immobilisation of enzymes and their use in biosensor development. *Analyst* 124:1181-1184.
- Selam, J. L. 1997. Management of diabetes with glucose sensors and implantable insulin pumps. From the dream of the 60s to the realities of the 90s. *ASAIO J*, 43:137-142.
- Service et al. 1970. Mean amplitude of glycemic excursions, a measure of diabetic instability. *Diabetes*, 19: 644-655.
- Service et al. 1987. Measurements of glucose control. *Diabetes Care*, 10: 225-237.
- Service, R. F. 2002. Can sensors make a home in the body? *Science* 297:962-3.
- Sharkawy et al. 1996. Engineering the tissue which encapsulates subcutaneous implants. I. Diffusion properties, *J Biomed Mater Res*, 37:401-412.
- Shaw et al. "In vitro testing of a simply constructed, highly stable glucose sensor suitable for implantation in diabetic patients," *Biosensors & Bioelectronics*, 6:401-406 (1991).
- Shichiri et al. 1982. Wearable artificial endocrine pancreas with needle-type glucose sensor. *Lancet* 2:1129-1131.
- Shichiri et al. 1986. Telemetry Glucose Monitoring Device with Needle-Type Glucose Sensor: A Useful Tool for Blood Glucose Monitoring in Diabetic Individuals. *Diabetes Care, Inc.* 9(3):298-301.
- Shichiri et al. 1983. Glycaemic Control in Pancreatectomized Dogs with a Wearable Artificial Endocrine Pancreas. *Diabetologia* 24:179-184.
- Shichiri et al. 1985. Needle-type Glucose Sensor for Wearable Artificial Endocrine Pancreas in Implantable Sensors 197-210.
- Shichiri et al. 1989. Membrane Design for Extending the Long-Life of an Implantable Glucose Sensor. *Diab. Nutr. Metab.* 2:309-313.
- Shults et al. 1994. A telemetry-instrumentation system for monitoring multiple subcutaneously implanted glucose sensors. *IEEE Transactions on Biomedical Engineering* 41(10):937-942.
- Sieminski et al. 2000. Biomaterial-microvasculature interactions. *Biomaterials* 21:2233-2241.
- Skyler, J. S. 2000. The economic burden of diabetes and the benefits of improved glycemic control: the potential role of a continuous glucose monitoring system. *Diabetes Technology & Therapeutics* 2 Suppl 1:S7-12.
- Slater-Maclean et al. 2008. Accuracy of glycemic measurements in the critically ill. *Diab. Thechnol. & Therapeut.*, 10:169-177.

(56)

**References Cited****OTHER PUBLICATIONS**

- Sokol et al. 1980. Immobilized-enzyme rate-determination method for glucose analysis. *Clin. Chem.* 26(1):89-92.
- Sriyudthsak et al. 1996. Enzyme-epoxy membrane based glucose analyzing system and medical applications. *Biosens Bioelectron* 11:735-742.
- Steil et al. 2003. Determination of plasma glucose during rapid glucose excursions with a subcutaneous glucose sensor. *Diabetes Technology & Therapeutics* 5(1):27-31.
- Stern et al., 1957. Electrochemical polarization: 1. A theoretical analysis of the shape of polarization curves, *Journal of the Electrochemical Society*, 104(1):56-63.
- Sternberg et al. 1988. Study and Development of Multilayer Needle-type Enzyme-based Glucose Microsensors. *Biosensors* 4:27-40.
- Sternberg et al. 1988. Covalent enzyme coupling on cellulose acetate membranes for glucose sensor development. *Anal. Chem.* 60: 2781-2786.
- Stokes. 1988. Polyether Polyurethanes: Biostable or Not? *J. Biomat. Appl.* 3:228-259.
- Sumino T. et al. 1998. Preliminary study of continuous glucose monitoring with a microdialysis technique. *Proceedings of the IEEE*, 20(4):1775-1778.
- Takegami et al. 1992. Pervaporation of ethanol water mixtures using novel hydrophobic membranes containing polydimethylsiloxane, *Journal of Membrane Science*, 75(93-105).
- Tanenberg et al. 2000. Continuous glucose monitoring system: A new approach to the diagnosis of diabetic gastroparesis. *Diabetes Technology & Therapeutics*, 2 Suppl 1:S73-80.
- Tang et al. 1993. Fibrin(ogen) mediates acute inflammatory responses to biomaterials. *J Exp Med* 178:2147-2156.
- Tang et al. 1995. Inflammatory responses to biomaterials. *Am J Clin Pathol* 103:466-471.
- Tang et al. 1996. Molecular determinants of acute inflammatory responses to biomaterials. *J Clin Invest* 97:1329-1334.
- Tang et al. 1998. Mast cells mediate acute inflammatory responses to implanted biomaterials. *Proc Natl Acad Sci U S A* 95:8841-8846.
- Tatsuma et al. 1991. Oxidase/peroxidase bilayer-modified electrodes as sensors for lactate, pyruvate, cholesterol and uric acid, *Analytica Chimica Acta*, 242:85-89.
- Thome et al. 1995. Can the decrease in subcutaneous glucose concentration precede the decrease in blood glucose level? Proposition for a push-pull kinetics hypothesis. *Norm. Metab. Res.* 27:53.
- Thomé-Duret et al. 1996. Modification of the sensitivity of glucose sensor implanted into subcutaneous tissue. *Diabetes Metabolism*, 22:174-178.
- Thome-Duret et al. 1996. Use of a subcutaneous glucose sensor to detect decreases in glucose concentration prior to observation in blood. *Anal. Chem.* 68:3822-3826.
- Thomé-Duret et al. 1998. Continuous glucose monitoring in the free-moving rat. *Metabolism*, 47:799-803.
- Thompson et al., *In Vivo Probes: Problems and Perspectives*, Department of Chemistry, University of Toronto, Canada, pp. 255-261, 1986.
- Tibell et al. 2001. Survival of macroencapsulated allogeneic parathyroid tissue one year after transplantation in nonimmunosuppressed humans. *Cell Transplant* 10:591-9.
- Tierney et al. 2000. Effect of acetaminophen on the accuracy of glucose measurements obtained with the GlucoWatch biographer. *Diabetes Technol Ther* 2:199-207.
- Tierney et al. 2000. The GlucoWatch® biographer: A frequent, automatic and noninvasive glucose monitor. *Ann. Med.* 32:632-641.
- Torjman et al., *Glucose monitoring in acute care: technologies on the horizon*, *Journal of Diabetes Science and Technology*, 2(2):178-181, Mar. 2008.
- Trecroci, D. 2002. A Glimpse into the Future—Continuous Monitoring of Glucose with a Microfiber. *Diabetes Interview* 42-43.
- Tse and Gough. 1987. Time-Dependent Inactivation of Immobilized Glucose Oxidase and Catalase. *Biotechnol. Bioeng.* 29:705-713.
- Turner and Pickup, "Diabetes mellitus: biosensors for research and management," *Biosensors*, 1:85-115 (1985).
- Turner et al. 1984. Carbon Monoxide: Acceptor Oxidoreductase from *Pseudomonas Thermocarboxydovorans* Strain C2 and its use in a Carbon Monoxide Sensor. *Analytica Chimica Acta*, 163: 161-174.
- Unger et al. 2004. Glucose control in the hospitalized patient. *Emerg Med* 36(9):12-18.
- Updike et al. 1967. The enzyme electrode. *Nature*, 214:986-988.
- Updike et al. 1979. Continuous glucose monitor based on an immobilized enzyme electrode detector. *J Lab Clin Med*, 93(4):518-527.
- Updike et al. 1982. Implanting the glucose enzyme electrode: Problems, progress, and alternative solutions. *Diabetes Care*, 5(3):207-212.
- Updike et al. 1988. Laboratory Evaluation of New Reusable Blood Glucose Sensor. *Diabetes Care*, 11:801-807.
- Updike et al. 1994. Enzymatic glucose sensor: Improved long-term performance in vitro and in vivo. *ASAIO Journal*, 40(2):157-163.
- Updike et al. 1997. Principles of long-term fully implanted sensors with emphasis on radiotelemetric monitoring of blood glucose form inside a subcutaneous foreign body capsule (FBC). In Fraser, ed., *Biosensors in the Body*. New York. John Wiley & Sons, pp. 117-137.
- Updike et al. 2000. A subcutaneous glucose sensor with improved longevity, dynamic range, and stability of calibration. *Diabetes Care* 23(2):208-214.
- Utah Medical Products Inc., *Blood Pressure Transducers product specifications*. 6 pp. 2003-2006, 2003.
- Vadgama, P. Nov. 1981. Enzyme electrodes as practical biosensors. *Journal of Medical Engineering & Technology* 5(6):293-298.
- Vadgama. 1988. Diffusion limited enzyme electrodes. *NATO ASI Series: Series C, Math and Phys. Sci.* 226:359-377.
- Van den Berghe 2004. Tight blood glucose control with insulin in "real-life" intensive care. *Mayo Clin Proc* 79(8):977-978.
- Velho et al. 1989. In vitro and in vivo stability of electrode potentials in needle-type glucose sensors. Influence of needle material. *Diabetes* 38:164-171.
- Velho et al. 1989. Strategies for calibrating a subcutaneous glucose sensor. *Biomed Biochim Acta* 48(11/12):957-964.
- von Woedtke et al. 1989. In situ calibration of implanted electrochemical glucose sensors. *Biomed Biochim. Acta* 48(11/12):943-952.
- Wagner et al. 1998. Continuous amperometric monitoring of glucose in a brittle diabetic chimpanzee with a miniature subcutaneous electrode. *Proc. Natl. Acad. Sci. A*, 95:6379-6382.
- Wang et al. 1994. Highly Selective Membrane-Free, Mediator-Free Glucose Biosensor. *Anal. Chem.* 66:3600-3603.
- Wang et al. 1997. Improved ruggedness for membrane-based amperometric sensors using a pulsed amperometric method. *Anal Chem* 69:4482-4489.
- Ward et al. 1999. Assessment of chronically implanted subcutaneous glucose sensors in dogs: the effect of surrounding fluid masses. *ASAIO Journal*, 45:555-561.
- Ward et al. 2004. A wire-based dual-analyte sensor for Glucose and Lactate: In Vitro and In Vivo Evaluation, *Diab Tech Therapeut.* 6(3): 389-401.
- Ward et al. 2000. Understanding Spontaneous Output Fluctuations of an Amperometric Glucose Sensor: Effect of Inhalation Anesthesia and e of a Nonenzyme Containing Electrode. *ASAIO Journal* 540-546.
- Ward et al. 2000. Rise in background current over time in a subcutaneous glucose sensor in the rabbit: Relevance to calibration and accuracy. *Biosensors & Bioelectronics*, 15:53-61.
- Ward et al. 2002. A new amperometric glucose microsensor: In vitro and short-term in vivo evaluation. *Biosensors & Bioelectronics*, 17:181-189.
- Wientjes, K. J. C. 2000. Development of a glucose sensor for diabetic patients (Ph.D. Thesis).
- Wikipedia 2006. "Intravenous therapy," [http://en.wikipedia.org/wiki/Intravenous\\_therapy](http://en.wikipedia.org/wiki/Intravenous_therapy), Aug. 15, 2006, 6 pp.
- Wiley Electrical and Electronics Engineering Dictionary. 2004. John Wiley & Sons, Inc. pp. 141, 142, 548, 549.
- Wilkins et al. 1988. The coated wire electrode glucose sensor, *Horm Metab Res Suppl.*, 20:50-55.

(56)

**References Cited**

## OTHER PUBLICATIONS

Wilkins et al. 1995. Glucose monitoring: state of the art and future possibilities. *Med Eng Phys* 18:273-288.

Wilkins et al. 1995. Integrated implantable device for long-term glucose monitoring. *Biosens. Bioelectron* 10:485-494.

Wilson et al. 1992. Progress toward the development of an implantable sensor for glucose. *Clin. Chem.* 38(9):1613-1617.

Wilson et al. 2000. Enzyme-based biosensors for in vivo measurements. *Chem. Rev.*, 100:2693-2704.

Wood, W. et al. Mar. 1990. Hermetic Sealing with Epoxy. *Mechanical Engineering* 1-3.

Woodward. 1982. How Fibroblasts and Giant Cells Encapsulate Implants: Considerations in Design of Glucose Sensor. *Diabetes Care* 5:278-281.

Wu et al. 1999. In site electrochemical oxygen generation with an immunoisolation device. *Annals New York Academy of Sciences*, pp. 105-125.

Yang et al (1996). "A glucose biosensor based on an oxygen electrode: In-vitro performances in a model buffer solution and in blood plasma," *Biomedical Instrumentation & Technology*, 30:55-61.

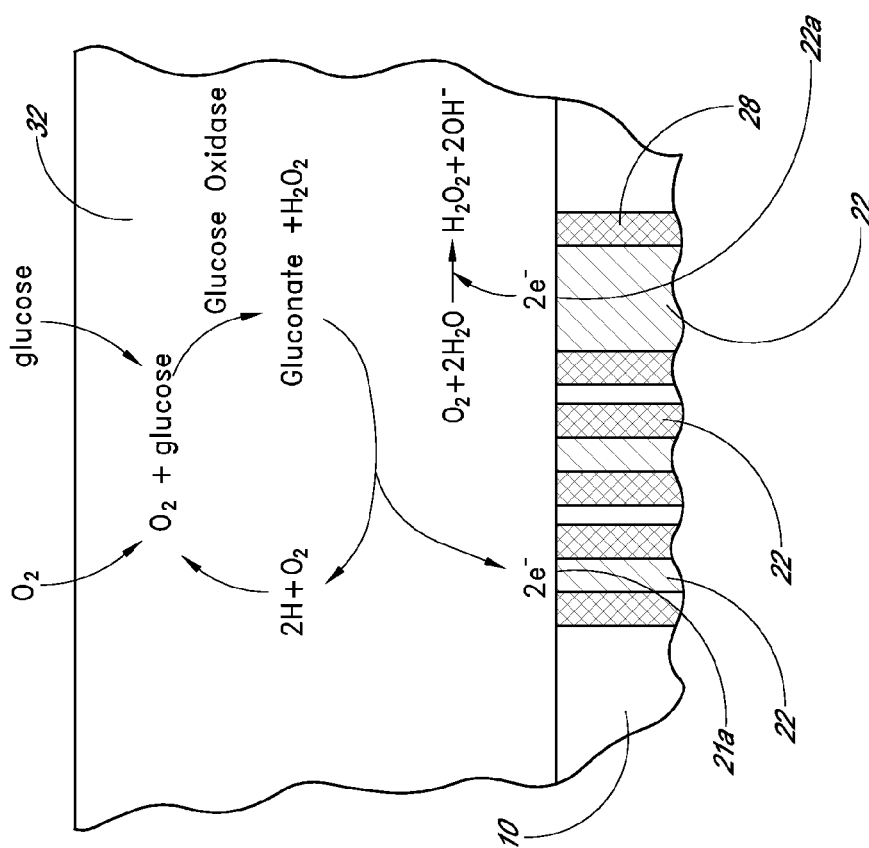
Yang et al. 1998. Development of needle-type glucose sensor with high selectivity. *Science and Actuators B* 46:249-256.

Zhang et al (1993). Electrochemical oxidation of H<sub>2</sub>O<sub>2</sub> on Pt and Pt + Ir electrodes in physiological buffer and its applicability to H<sub>2</sub>O<sub>2</sub>-based biosensors. *J. Electroanal. Chem.*, 345:253-271.

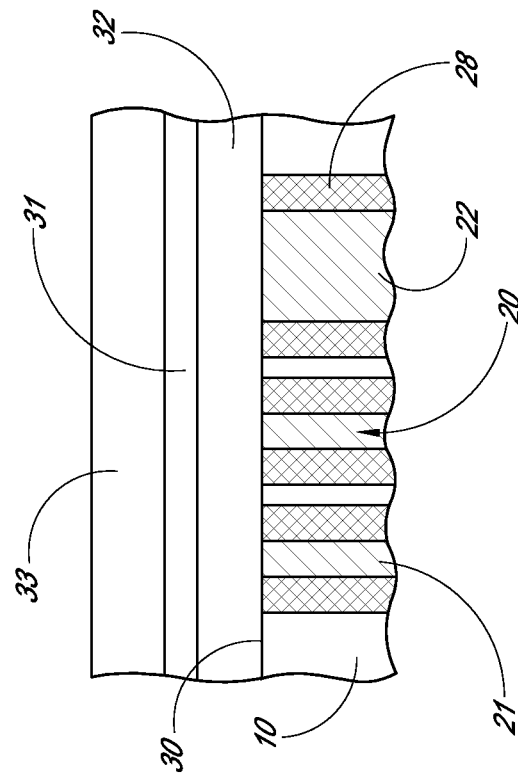
Zhu et al. (1994). "Fabrication and characterization of glucose sensors based on a microarray H<sub>2</sub>O<sub>2</sub> electrode." *Biosensors & Bioelectronics*, 9: 295-300.

\* cited by examiner

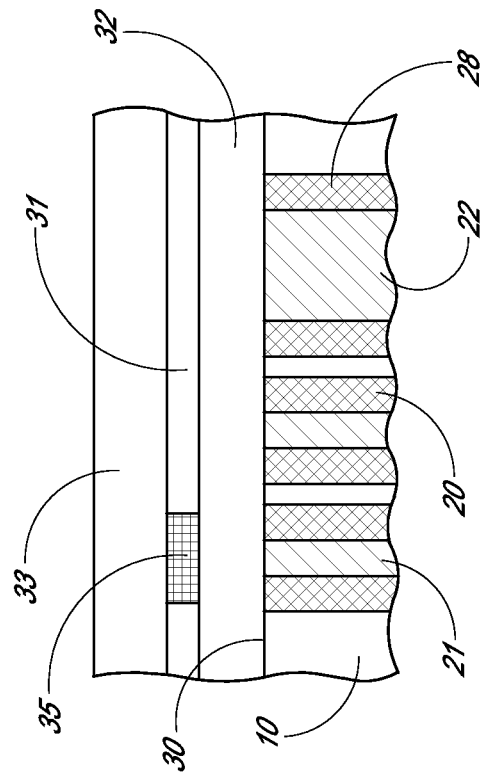




**FIG. 1**



*FIG. 2A*



*FIG. 2B*

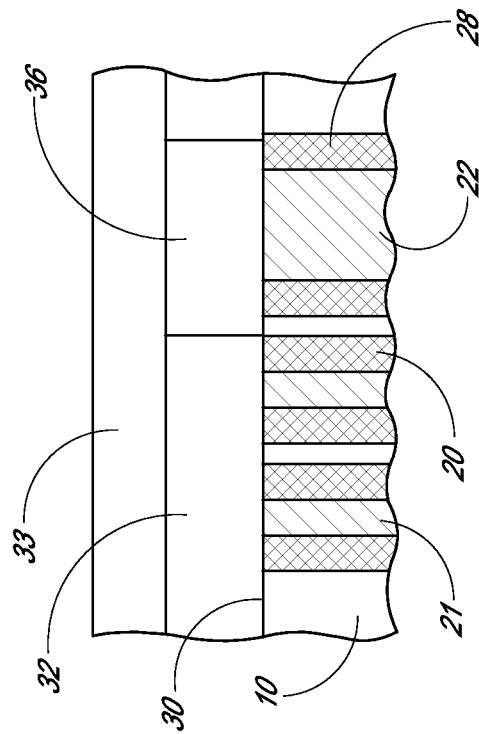
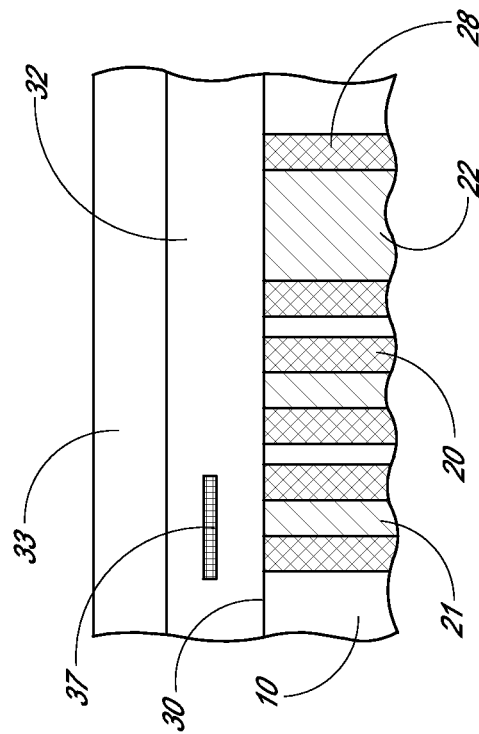
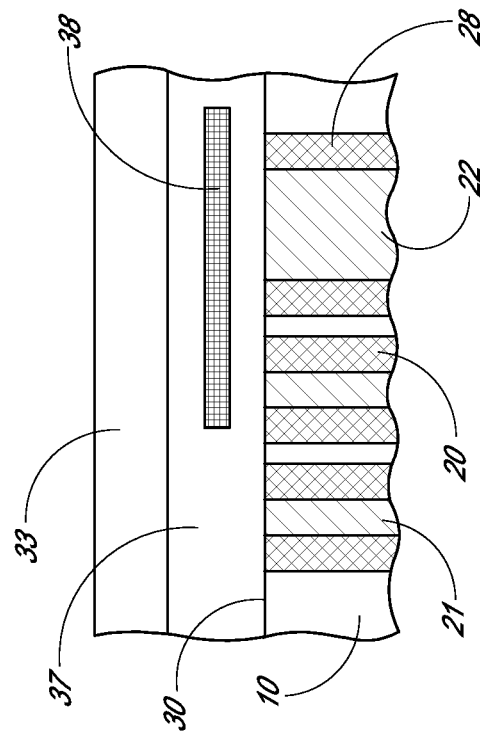


FIG. 2C



*FIG. 2D*



*FIG. 2E*

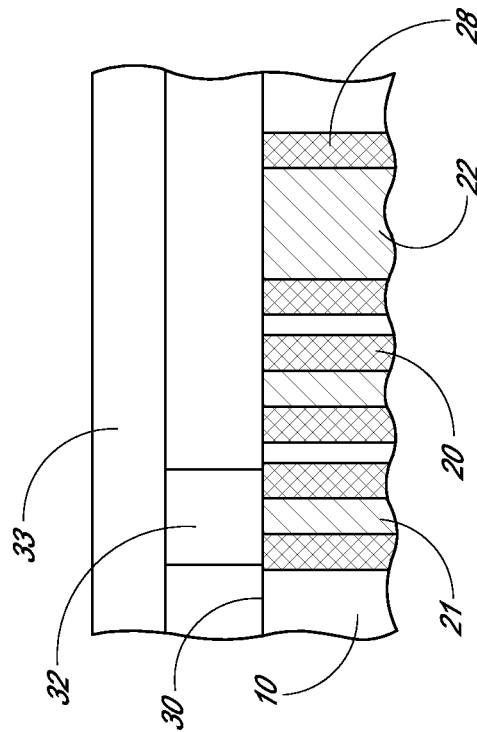


FIG. 2F

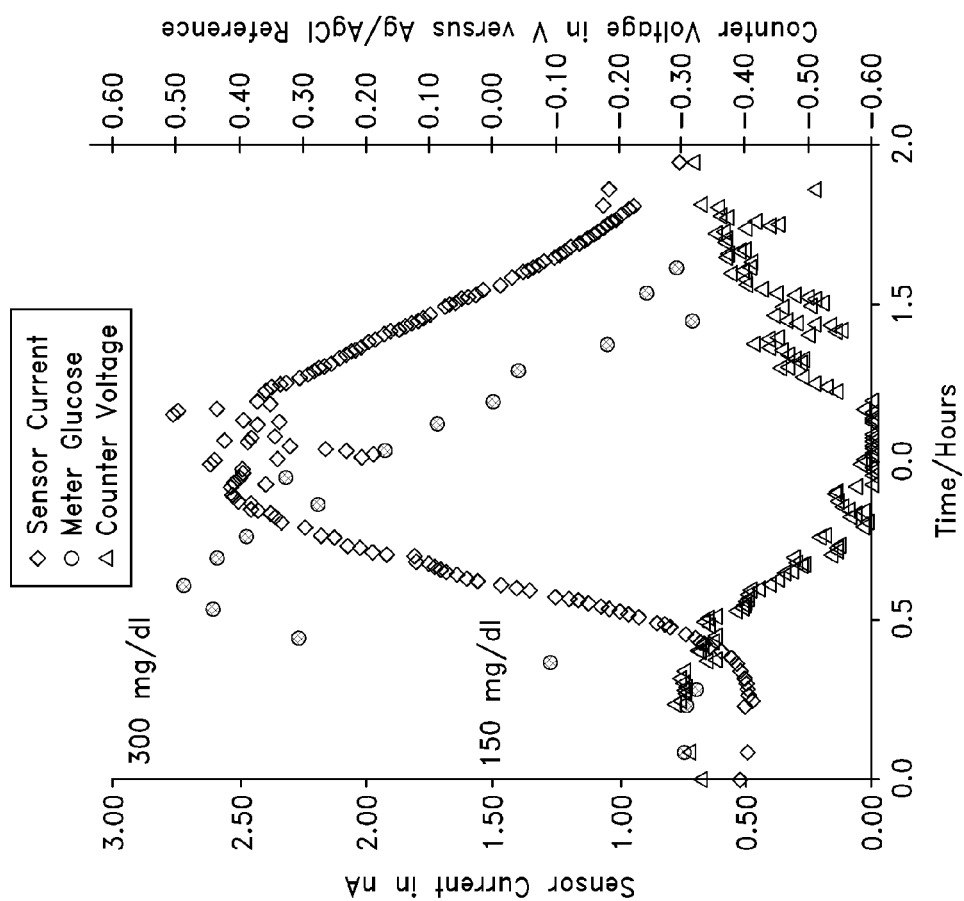


FIG. 3



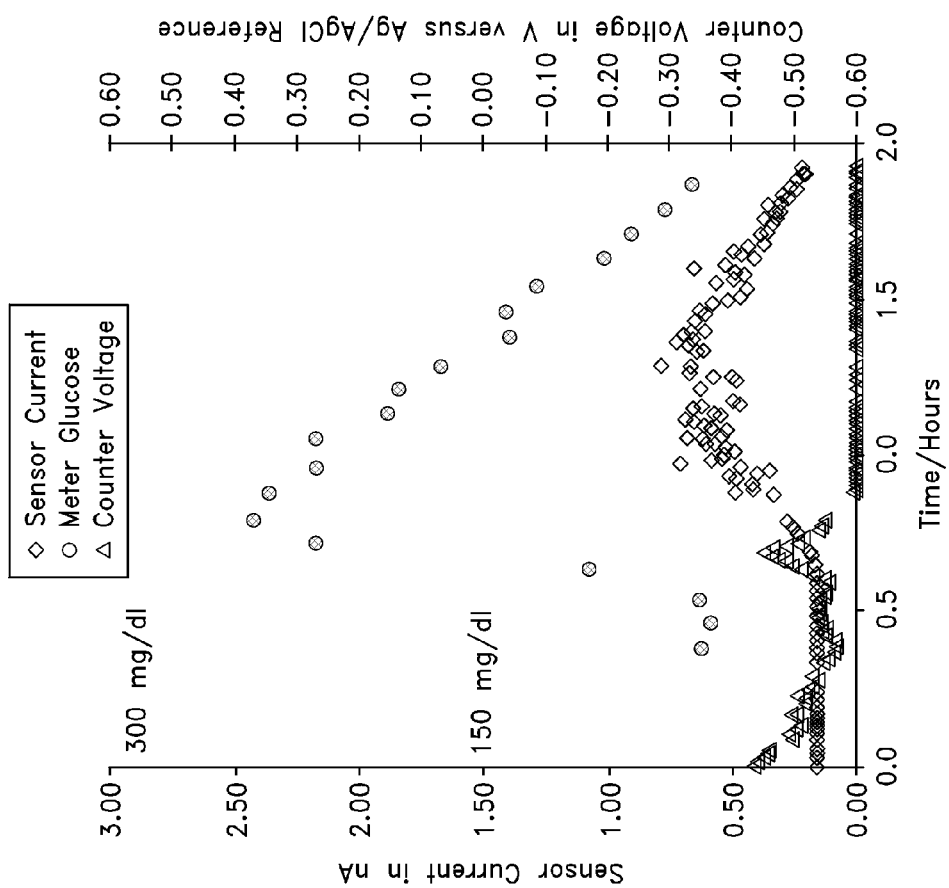


FIG. 4

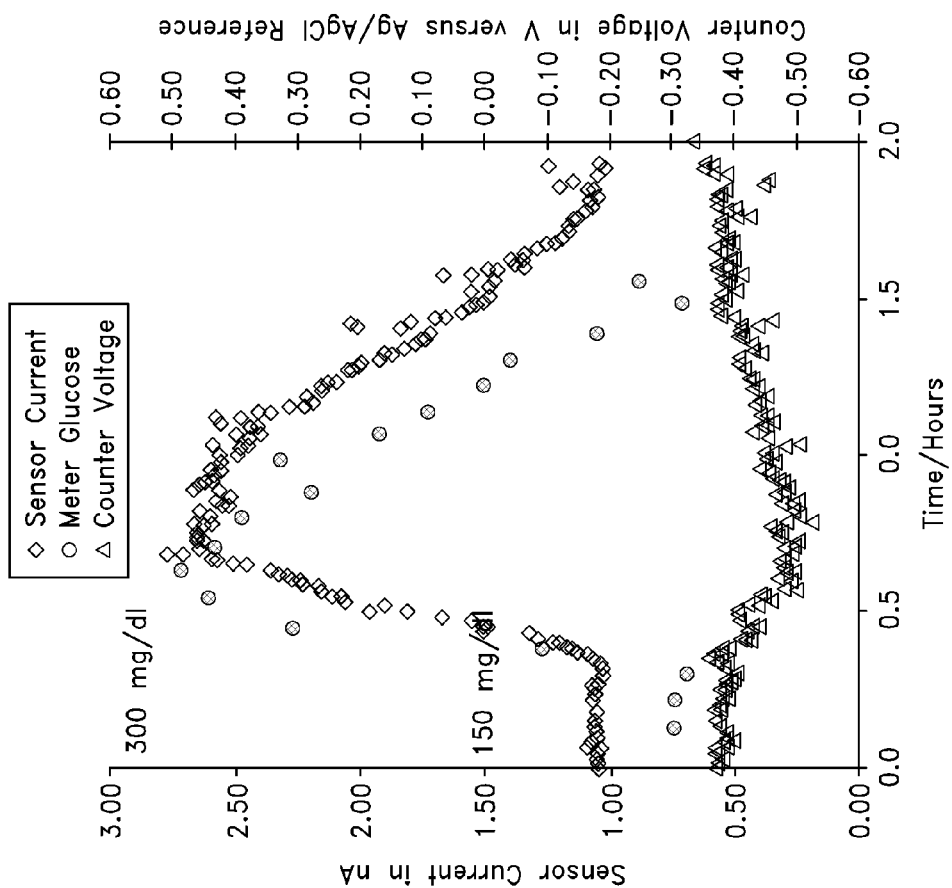


FIG. 5

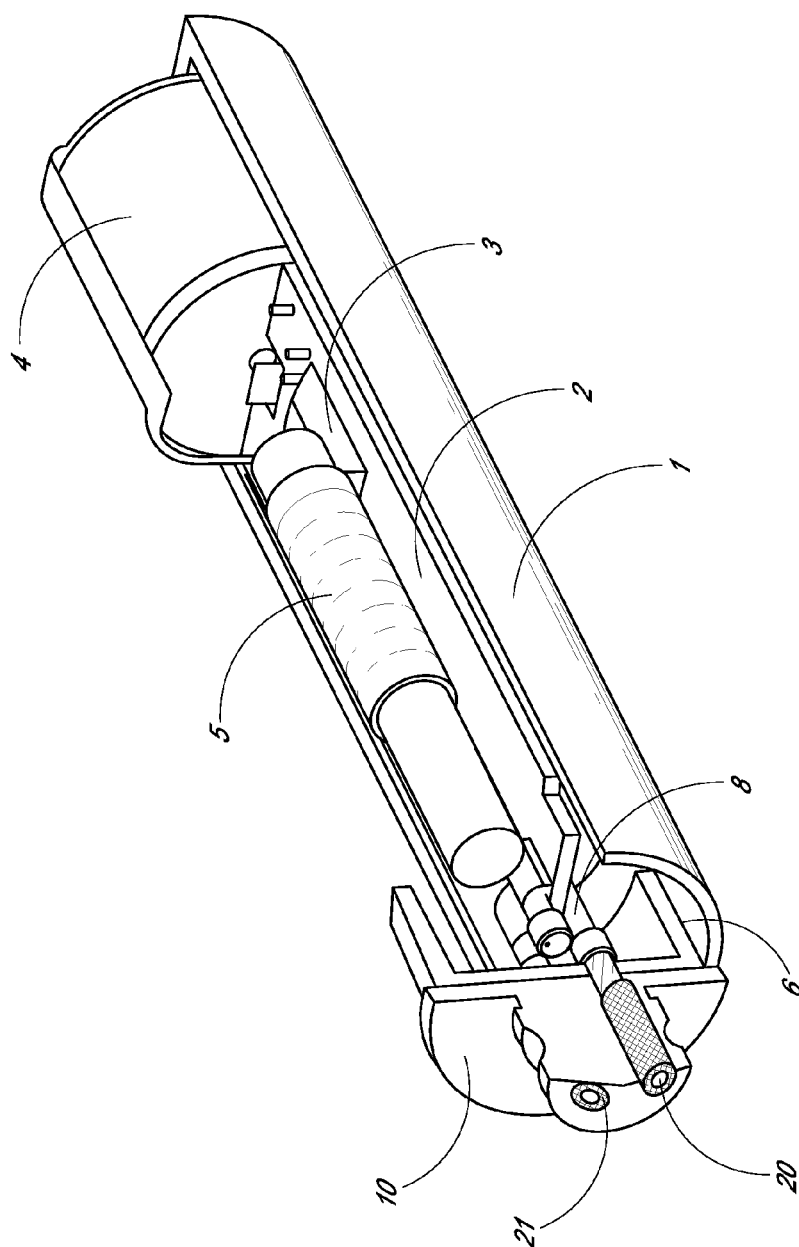
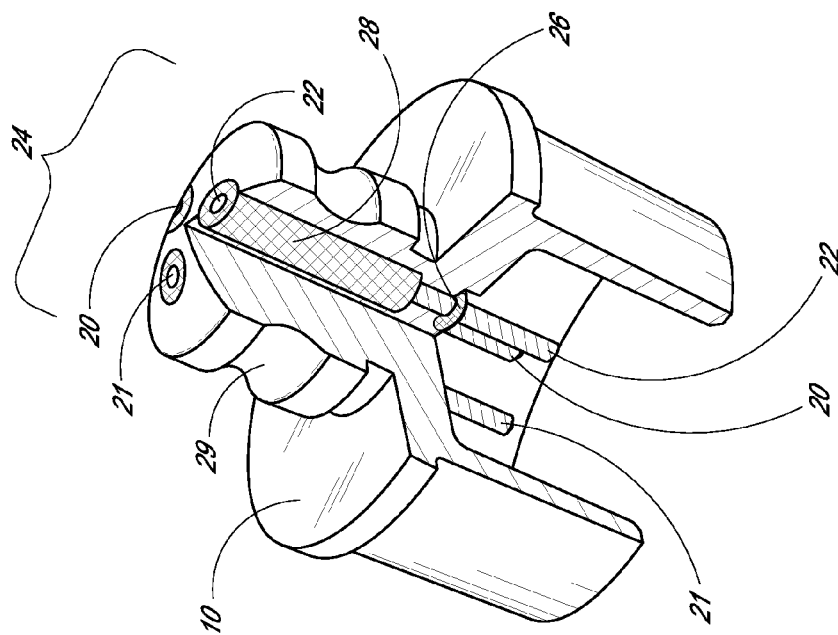


FIG. 6A



**FIG. 6B**

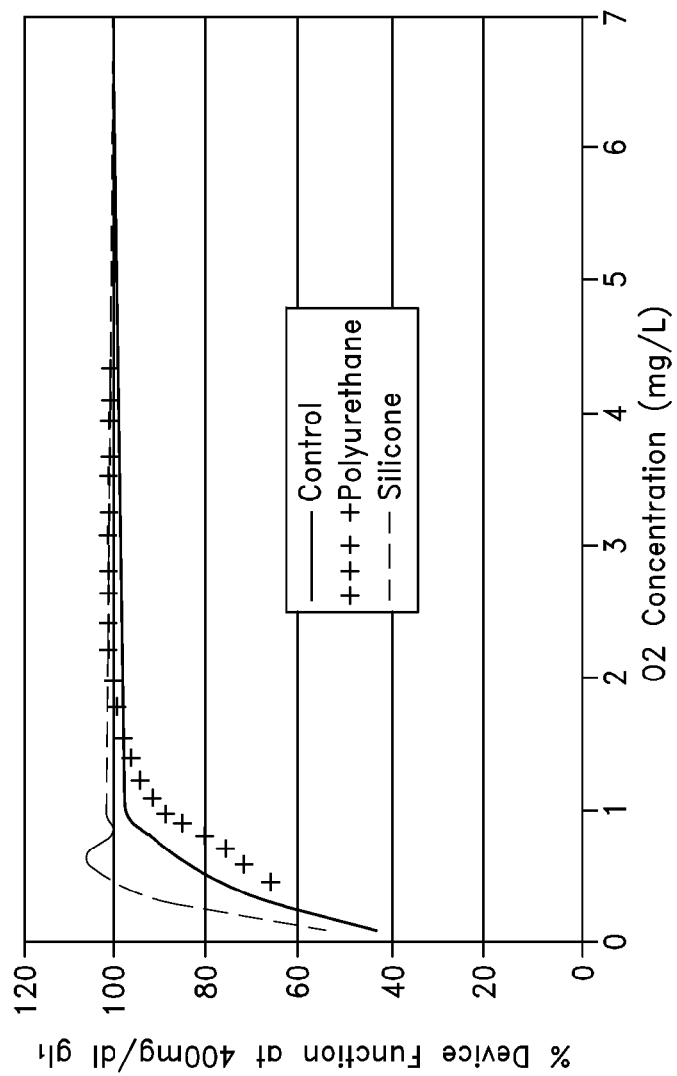
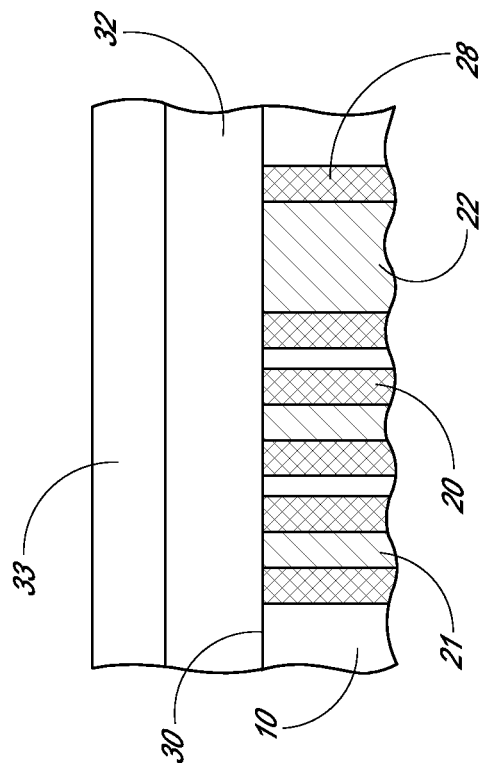


FIG. 7



*FIG. 8*

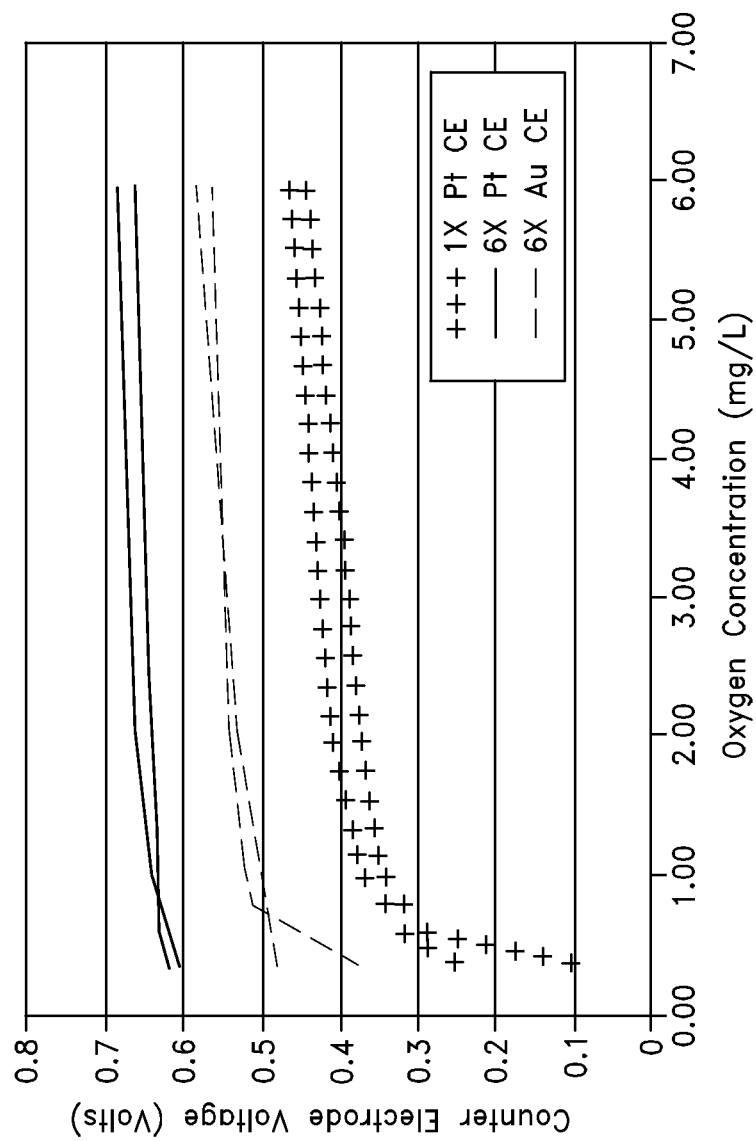


FIG. 9

# SENSOR HEAD FOR USE WITH IMPLANTABLE DEVICES

## INCORPORATION BY REFERENCE TO RELATED APPLICATIONS

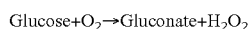
Any and all priority claims identified in the Application Data Sheet, or any correction thereto, are hereby incorporated by reference under 37 CFR 1.57. This application is a continuation of U.S. application Ser. No. 12/260,017, filed on Oct. 28, 2008, which is a division of U.S. application Ser. No. 11/021,162, filed Dec. 22, 2004, now U.S. Pat. No. 7,471,972, which is a continuation of U.S. application Ser. No. 09/916,711, filed Jul. 27, 2001, now abandoned. Each of the aforementioned applications is incorporated by reference herein in its entirety, and each is hereby expressly made a part of this specification.

## FIELD OF THE INVENTION

The present invention relates generally to novel sensor heads utilized with implantable devices, devices including these sensor heads and methods for determining analyte levels using these implantable devices. More particularly, the invention relates to sensor heads, implantable devices including these sensor heads and methods for monitoring glucose levels in a biological fluid using these devices.

## BACKGROUND OF THE INVENTION

Amperometric electrochemical sensors require a counter electrode to balance the current generated by the species being measured at the working electrode. In the case of a glucose oxidase based glucose sensor, the species being measured at the working electrode is  $H_2O_2$ . Glucose oxidase catalyzes the conversion of oxygen and glucose to hydrogen peroxide and gluconate according to the following reaction:



Because for each glucose molecule metabolized, there is a proportional change in the product  $H_2O_2$ , one can monitor the change in  $H_2O_2$  to determine glucose concentration. Oxidation of  $H_2O_2$  by the working electrode is balanced by reduction of ambient oxygen, enzyme generated  $H_2O_2$ , or other reducible species at the counter electrode. In vivo glucose concentration may vary from about one hundred times or more that of the oxygen concentration. Consequently, oxygen becomes a limiting reactant in the electrochemical reaction and when insufficient oxygen is provided to the sensor, the sensor will be unable to accurately measure glucose concentration. Those skilled in the art have come to interpret oxygen limitations resulting in depressed function as being a problem of availability of oxygen to the enzyme.

As shown in FIG. 1, the sensor head 10 includes a working electrode 21 (anode), counter electrode 22 (cathode), and reference electrode 20 which are affixed to the head by both brazing 26 the electrode metal to the ceramic and potting with epoxy 28. The working electrode 21 (anode) and counter-electrode 22 (cathode) of a glucose oxidase-based glucose sensor head 10 require oxygen in different capacities. Prior art teaches an enzyme-containing membrane that resides above an amperometric electrochemical sensor. In FIG. 1, region 32 includes an immobilized enzyme, i.e. glucose oxidase. Within the enzyme layer above the working electrode 21, oxygen is required for the production of  $H_2O_2$  from glucose. The  $H_2O_2$  produced from the glucose oxidase reaction further reacts at surface 21a of working electrode 21 and

produces two electrons. The products of this reaction are two protons ( $2H_+$ ), two electrons ( $2e^-$ ), and one oxygen molecule ( $O_2$ ) (Fraser, D. M. "An Introduction to In Vivo Biosensing: Progress and problems." In "Biosensors and the Body," D. M. Fraser, ed., 1997, pp. 1-56 John Wiley and Sons, New York). In theory, the oxygen concentration near the working electrode 21, which is consumed during the glucose oxidase reaction, is replenished by the second reaction at the working electrode. Therefore, the net consumption of oxygen is zero. In practice, neither all of the  $H_2O_2$  produced by the enzyme diffuses to the working electrode surface nor does all of the oxygen produced at the electrode diffuse to the enzyme domain.

With further reference to FIG. 1, the counter electrode 22 utilizes oxygen as an electron acceptor. The most likely reducible species for this system are oxygen or enzyme generated peroxide (Fraser, D. M. supra). There are two main pathways by which oxygen may be consumed at the counter electrode 22. These are a four-electron pathway to produce hydroxide and a two-electron pathway to produce hydrogen peroxide. The two-electron pathway is shown in FIG. 1. Oxygen is further consumed above the counter electrode by the glucose oxidase in region 32. Due to the oxygen consumption by both the enzyme and the counter electrode, there is a net consumption of oxygen at the surface 22a of the counter electrode. Theoretically, in the domain of the working electrode there is significantly less net loss of oxygen than in the region of the counter electrode. In addition, there is a close correlation between the ability of the counter electrode to maintain current balance and sensor function. Taken together, it appears that counter electrode function becomes limited before the enzyme reaction becomes limited when oxygen concentration is lowered.

Those practicing in the field of implantable glucose oxidase sensors have focused on improving sensor function by increasing the local concentration of oxygen in the region of the working electrode. (Fraser, D. M. supra).

We have observed that in some cases, loss of glucose oxidase sensor function may not be due to a limitation of oxygen in the enzyme layer near the working electrode, but may instead be due to a limitation of oxygen at the counter electrode. In the presence of increasing glucose concentrations, a higher peroxide concentration results, thereby increasing the current at the working electrode. When this occurs, the counter electrode limitation begins to manifest itself as this electrode moves to increasingly negative voltages in the search for reducible species. When a sufficient supply of reducible species, such as oxygen, are not available, the counter electrode voltage reaches a circuitry limit of  $-0.6V$  resulting in compromised sensor function (see FIG. 3).

FIG. 3 shows simultaneous measurement of counter-electrode voltage and sensor output to glucose levels from a glucose sensor implanted subcutaneously in a canine host. It can be observed that as glucose levels increase, the counter electrode voltage decreases. When the counter electrode voltage reaches  $-0.6V$ , the signal to noise ratio increases significantly. This reduces the accuracy of the device. FIG. 4 shows a further example of another glucose sensor in which the counter-electrode reaches the circuitry limit. Again, once the counter electrode reaches  $-0.6V$ , the sensitivity and/or signal to noise ratio of the device is compromised. In both of these examples, glucose levels reached nearly 300 mg/dl. However, in FIG. 3 the sensor showed a greater than three-fold higher current output than the sensor in FIG. 4. These data suggest that there may be a limitation of reducible species at the counter electrode, which may limit the sensitivity of the device as the glucose levels increase. In contrast, FIG. 5



shows a glucose sensor in which the counter electrode voltage did not reach  $-0.6\text{V}$ . In FIG. 5 it can be observed that the sensor was able to maintain a current balance between the working and counter electrodes, thereby enabling accurate measurements throughout the course of the experiment. The results shown in FIGS. 3, 4 and 5 led the present inventors to postulate that by keeping the counter electrode from reaching the circuitry limit, one could maintain sensitivity and accuracy of the device.

Two approaches have been utilized by others to relieve the counter electrode limitation described above. The first approach involves the widening of the potential range over which the counter electrode can move in the negative direction to avoid reaching circuitry limitations. Unfortunately, this approach increases undesirable products that are produced at lower potentials. One such product, hydrogen, may form at the counter electrode, which may then diffuse back to the working electrode. This may contribute to additional current resulting in erroneously high glucose concentration readings. Additionally, at these increasingly negative potentials, the probability of passivating or poisoning the counter electrode greatly increases. This effectively reduces the counter electrode surface area requiring a higher current density at the remaining area to maintain current balance. Furthermore, increased current load increases the negative potentials eventually resulting in electrode failure.

The second approach is utilizing the metal case of the device as a counter electrode (see U.S. Pat. No. 4,671,288, Gough or U.S. Pat. No. 5,914,026, Blubaugh). This provides an initial excess in surface area which is expected to serve the current balancing needs of the device over its lifetime. However, when the counter electrode reaction is a reduction reaction, as in Blubaugh, the normally present metal oxide layer will be reduced to bare metal over time leaving the surface subject to corrosion, poisoning, and eventual cascade failure. This problem is magnified when considering the various constituents of the body fluid that the metal casing is exposed to during in vivo use. To date, there has been no demonstration of long-term performance of such a device with this counter electrode geometry.

Consequently, there is a need for a sensor that will provide accurate analyte measurements, that reduces the potential for cascade failure due to increasing negative potentials, corrosion and poisoning, and that will function effectively and efficiently in low oxygen concentration environments.

### SUMMARY OF THE INVENTION

In one aspect of the present invention, a sensor head for use in a device that measures the concentration of an analyte in a biological fluid is provided that includes a non-conductive body; a working electrode, a reference electrode and a counter electrode, wherein the electrodes pass through the non-conductive body forming an electrochemically reactive surface at one location on the body and forming an electronic connection at another location on the body, and further wherein the electrochemically reactive surface of the counter electrode is greater than the surface area of the working electrode; and a multi-region membrane affixed to the non-conductive body and covering the working electrode, reference electrode and counter electrode.

In another aspect of the present invention, a sensor head for use in an implantable analyte measuring device is provided which includes the same sensor head components as those described above.

The sensor heads of the present invention include a multi-region membrane that controls the number of species that are

able to reach the surface of the electrodes. In particular, such a membrane allows the passage of desired substrate molecules (e.g. oxygen and glucose) and rejects other larger molecules that may interfere with accurate detection of an analyte. The sensor heads of the present invention also provide a larger counter electrode reactive surface that balances the current between the working and counter electrodes, thereby minimizing negative potential extremes that may interfere with accurate analyte detection.

In another aspect of the present invention, an implantable device for measuring an analyte in a biological fluid is provided including at least one of the sensor heads described above. In still another aspect of the present invention, a method of monitoring glucose levels is disclosed which includes the steps of providing a host, and an implantable device as provided above and implanting the device in the host.

Further encompassed by the invention is a method of measuring glucose in a biological fluid including the steps of providing a host and a implantable device described above, which includes a sensor head capable of accurate continuous glucose sensing; and implanting the device in the host.

The sensor head, membrane architectures, devices and methods of the present invention allow for the collection of continuous information regarding desired analyte levels (e.g. glucose). Such continuous information enables the determination of trends in glucose levels, which can be extremely important in the management of diabetic patients.

### DEFINITIONS

In order to facilitate an understanding of the present invention, a number of terms are defined below.

The term "sensor head" refers to the region of a monitoring device responsible for the detection of a particular analyte. The sensor head generally comprises a non-conductive body, a working electrode (anode), a reference electrode and a counter electrode (cathode) passing through and secured within the body forming an electrochemically reactive surface at one location on the body and an electronic connective means at another location on the body, and a multi-region membrane affixed to the body and covering the electrochemically reactive surface. The counter electrode has a greater electrochemically reactive surface area than the working electrode. During general operation of the sensor a biological sample (e.g., blood or interstitial fluid) or a portion thereof contacts (directly or after passage through one or more membranes or domains) an enzyme (e.g., glucose oxidase); the reaction of the biological sample (or portion thereof) results in the formation of reaction products that allow a determination of the analyte (e.g. glucose) level in the biological sample. In preferred embodiments of the present invention, the multi-region membrane further comprises an enzyme domain, and an electrolyte phase (i.e., a free-flowing liquid phase comprising an electrolyte-containing fluid described further below).

The term "analyte" refers to a substance or chemical constituent in a biological fluid (e.g., blood, interstitial fluid, cerebral spinal fluid, lymph fluid or urine) that can be analyzed. A preferred analyte for measurement by the sensor heads, devices and methods of the present invention is glucose.

The term "electrochemically reactive surface" refers to the surface of an electrode where an electrochemical reaction takes place. In the case of the working electrode, the hydrogen peroxide produced by the enzyme catalyzed reaction of the analyte being detected reacts creating a measurable electronic

current (e.g. detection of glucose analyte utilizing glucose oxidase produces  $H_2O_2$  peroxide as a by product,  $H_2O_2$  reacts with the surface of the working electrode producing two protons ( $2H_+$ ), two electrons ( $2e^-$ ) and one molecule of oxygen ( $O_2$ ) which produces the electronic current being detected). In the case of the counter electrode, a reducible species, e.g.  $O_2$  is reduced at the electrode surface in order to balance the current being generated by the working electrode.

The term "electronic connection" refers to any electronic connection known to those in the art that may be utilized to interface the sensor head electrodes with the electronic circuitry of a device such as mechanical (e.g., pin and socket) or soldered.

The term "domain" refers to regions of the membrane of the present invention that may be layers, uniform or non-uniform gradients (e.g. anisotropic) or provided as portions of the membrane.

The term "multi-region membrane" refers to a permeable membrane that may be comprised of two or more domains and constructed of biomaterials of a few microns thickness or more which are permeable to oxygen and may or may not be permeable to glucose. One of the membranes may be placed over the sensor body to keep host cells (e.g., macrophages) from gaining proximity to, and thereby damaging, the enzyme membrane or forming a barrier cell layer and interfering with the transport of analyte across the tissue-device interface.

The phrase "distant from" refers to the spatial relationship between various elements in comparison to a particular point of reference. For example, some embodiments of a biological fluid measuring device comprise a multi-region membrane that may be comprised of a number of domains. If the electrodes of the sensor head are deemed to be the point of reference, and one of the multi-region membrane domains is positioned farther from the electrodes, than that domain is distant from the electrodes.

The term "oxygen antenna domain" and the like refers to a domain composed of a material that has higher oxygen solubility than aqueous media so that it concentrates oxygen from the biological fluid surrounding the biointerface membrane. The domain can then act as an oxygen reservoir during times of minimal oxygen need and has the capacity to provide on demand a higher oxygen gradient to facilitate oxygen transport across the membrane. This enhances function in the enzyme reaction domain and at the counter electrode surface when glucose conversion to hydrogen peroxide in the enzyme domain consumes oxygen from the surrounding domains. Thus, this ability of the oxygen antenna domain to apply a higher flux of oxygen to critical domains when needed improves overall sensor function.

The term "solid portions" and the like refer to a material having a structure that may or may not have an open-cell configuration but in either case prohibits whole cells from traveling through or residing within the material.

The term "substantial number" refers to the number of cavities or solid portions having a particular size within a domain in which greater than 50 percent of all cavities or solid portions are of the specified size, preferably greater than 75 percent and most preferably greater than 90 percent of the cavities or solid portions have the specified size.

The term "co-continuous" and the like refers to a solid portion wherein an unbroken curved line in three dimensions exists between any two points of the solid portion.

The term "host" refers to both humans and animals.

The term "accurately" means, for example, 90% of measured glucose values are within the "A" and "B" region of a standard Clarke error grid when the sensor measurements are

compared to a standard reference measurement. It is understood that like any analytical device, calibration, calibration validation and recalibration are required for the most accurate operation of the device.

The phrase "continuous glucose sensing" refers to the period in which monitoring of plasma glucose concentration is continuously performed, for example, about every 10 minutes.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 Illustration of thermodynamically favored reactions at the working electrode and counter electrode at the desired voltage potentials.

FIG. 2A depicts a cross-sectional exploded view of a sensor head of the present invention wherein the multi-region membrane comprises three regions.

FIG. 2B depicts a cross-sectional exploded view of a sensor head of the present invention wherein a portion of the second membrane region does not cover the working electrode.

FIG. 2C depicts a cross-sectional exploded view of a sensor head of the present invention which includes two distinct regions, wherein the region adjacent the electrochemically reactive surfaces includes a portion positioned over the counter electrode which corresponds to a silicone domain.

FIG. 2D depicts a cross-sectional exploded view of a sensor head of the present invention wherein an active enzyme of the immobilized enzyme domain is positioned only over the working electrode.

FIG. 2E depicts a cross-sectional exploded view of a sensor head of the present invention wherein the enzyme positioned over the counter electrode has been inactivated.

FIG. 2F depicts a cross-sectional exploded view of a sensor head of the present invention wherein the membrane region containing immobilized enzyme is positioned only over the working electrode.

FIG. 3 Illustration of an implantable glucose sensor's ability to measure glucose concentration during an infusion study in a canine when the counter electrode voltage drops to the electronic circuitry limit at approximately 0.75 hours wherein the sensor current output reaches 2.50 nA.

FIG. 4 Illustration of an implantable glucose sensor's ability to measure glucose concentration during an infusion study in a canine when the counter electrode voltage drops to the electronic circuitry limit after 0.5 hours wherein the sensor current output reaches 0.50 nA.

FIG. 5 Illustration of an implantable glucose sensor's ability to measure glucose concentration during an infusion study in a canine when the counter electrode voltage is maintained above the electronic circuitry limit.

FIG. 6A shows a schematic representation of a cylindrical analyte measuring device including a sensor head according to the present invention.

FIG. 6B is an exploded view of the sensor head of the device shown in FIG. 6A.

FIG. 7 Graphical representation of the function of a device of the present invention utilizing the multi-region membrane architecture of FIG. 2B in vitro at 400 mg/dL glucose.

FIG. 8 depicts a cross-sectional exploded view of the electrode and membrane regions of a prior sensor device where the electrochemical reactive surface of the counter electrode is substantially equal to the surface area of the working electrode.

FIG. 9 Graphical representation of the counter electrode voltage as a function of oxygen concentration at 400 mg/dL glucose for sensor devices including the membrane shown in FIG. 8.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

In a preferred embodiment, the sensor heads, devices and methods of the present invention may be used to determine the level of glucose or other analytes in a host. The level of glucose is a particularly important measurement for individuals having diabetes in that effective treatment depends on the accuracy of this measurement.

The present invention increases the effectiveness of counter electrode function by a method that does not depend on increasing the local concentration of oxygen. In a preferred embodiment, the counter electrode has an electrochemical reactive surface area greater than twice the surface area of the working electrode thereby substantially increasing the electrodes ability to utilize oxygen as a substrate. Further enhancement of the counter electrode's activity may be achieved if the electrode were made of gold. In a second preferred embodiment, the counter electrode has a textured surface, with surface topography that increases the surface area of the electrode while the diameter of the electrode remains constant. In a third preferred embodiment, the proximity of the glucose oxidase enzyme to the counter electrode may be decreased. Since the enzyme depletes oxygen locally, the counter electrode would best be situated at a location distant from the enzyme. This could be achieved by depleting the enzyme from or inactivating the enzyme located in the region near and over the counter electrode by methods known to those skilled in the art such as laser ablation, or chemical ablation. Alternatively, the membrane could be covered with an additional domain where glucose is selectively blocked from the area over the counter electrode.

In particular, the present invention reduces the potential for electrode poisoning by positioning all electrodes underneath a multi-region membrane so that there is control of the species reaching the electrode surfaces. These membranes allow passage of dissolved oxygen to support the counter electrode reactions at reasonable negative potentials while rejecting larger molecules which when reduced would coat the surface of the counter electrode eventually leading to cascade failure. The positioning of the counter electrode underneath the membrane assures that all currents are passing through the same conductive media, thereby reducing voltage losses due to membrane or solution resistance. In addition, the counter electrode will be able to collect enough species for the balancing current while minimizing the need to move towards negative potential extremes.

Although the description that follows is primarily directed at glucose monitoring sensor heads, devices and methods for their use, the sensor heads, devices and methods of the present invention are not limited to glucose measurement. Rather, the devices and methods may be applied to detect and quantitate other analytes present in biological fluids (including, but not limited to, amino acids and lactate), especially those analytes that are substrates for oxidase enzymes [see, e.g., U.S. Pat. No. 4,703,756 to Gough et al., hereby incorporated by reference].

## I. Nature of the Foreign Body Capsule

Devices and probes that are implanted into subcutaneous tissue will almost always elicit a foreign body capsule (FBC) as part of the body's response to the introduction of a foreign material. Therefore, implantation of a glucose sensor results in an acute inflammatory reaction followed by building of fibrotic tissue. Ultimately, a mature FBC comprising primarily a vascular fibrous tissue forms around the device (Shanker and Greisler, *Inflammation and Biomaterials in*

Greco R S, ed. *Implantation Biology: The Host Response and Biomedical Devices*, pp 68-80, CRC Press (1994)).

In general, the formation of a FBC has precluded the collection of reliable, continuous information, reportedly because of poor vascularization (Updike, S. J. et al., "Principles of Long-term Fully Implanted Sensors with Emphasis on Radiotelemetric Monitoring of Blood Glucose from inside a Subcutaneous Foreign Body Capsule (FBC)" in "Biosensors and the Body," D. M. Fraser, ed., 1997, pp. 117-38, John Wiley and Sons, New York). Thus, those skilled in the art have previously attempted to minimize FBC formation by, for example, using a short-lived needle geometry or sensor coatings to minimize the foreign body.

In contrast to the prior art, the teachings of the present invention recognize that FBC formation is the dominant event surrounding long-term implantation of any sensor and must be managed to support, rather than hinder or block, sensor performance. It has been observed that during the early periods following implantation of an analyte sensing device, particularly a glucose sensing device, that glucose sensors function well. However, after a few days to two or more weeks of implantation, these devices lose their function.

We have observed that this lack of sensor function is most likely due to cells (barrier cells) that associate with the outer surface of the device and physically block the transport of glucose into the device (i.e. form a barrier cell layer). Increased vascularization would not be expected to overcome this blockage. The present invention contemplates the use of particular biointerface membrane architectures that interfere with barrier cell layer formation on the membrane's surface. The present invention also contemplates the use of these membranes with a variety of implantable devices (e.g. analyte measuring devices particularly glucose measuring devices).

## II. The Sensor Head

In one embodiment of the sensor head of the invention, the body is made of a non-conductive material such as ceramic, glass, or polymer.

In a preferred embodiment, the sensor head interface region may include several different layers and/or membranes that cover and protect the electrodes of an implantable analyte-measuring device. The characteristics of these layers and/or membranes are now discussed in more detail. The layers and/or membranes prevent direct contact of the biological fluid sample with the electrodes, while permitting selected substances (e.g., analytes) of the fluid to pass through for reaction in an enzyme rich domain with subsequent electrochemical reaction of formed products at the electrodes.

It is well known in the art that electrode surfaces exposed to a wide range of biological molecules may suffer poisoning of catalytic activity and possible corrosion that could result in failure. However, utilizing the unique multi-region membrane architectures of the present invention, the active electrochemical surfaces of the sensor electrodes are preserved, retaining activity for extended periods of time in vivo. By limiting access to the electrochemically reactive surface of the electrodes to a small number of molecular species such as, for example, molecules having a molecular weight of about 34 Daltons (the molecular weight of peroxide) or less, only a small subset of the many molecular species present in biological fluids are permitted to contact the sensor. Use of such membranes has enabled sustained function of devices for over one year in vivo.

## A. Multi-Region Membrane

The multi-region membrane is constructed of two or more regions. The multi-region membrane may be provided in a number of different architectures. In one architecture, the

multi-region membrane includes a first region distant from the electrochemically reactive surfaces, a second region less distant from the electrochemically reactive surfaces and a third region adjacent to the electrochemically reactive surfaces. The first region includes a cell disruptive domain distant from the electrochemically reactive surfaces and a cell impermeable domain less distant from the electrochemically reactive surfaces. The second region is a glucose exclusion domain and the third region includes a resistance domain distant from the electrochemically reactive surfaces, an immobilized enzyme domain less distant from the electrochemically reactive surfaces, an interference domain less distant from the electrochemically reactive surfaces than the immobilized enzyme domain and a hydrogel domain adjacent to the electrochemically reactive surfaces.

In another architecture, the multi-region membrane includes a first region distant from the electrochemically reactive surfaces and a further region less distant from the electrochemically reactive surfaces. The first region includes a cell disruptive domain and a cell impermeable domain as described above. The "further region" includes a resistance domain, immobilized enzyme domain, interference domain, and hydrogel domain and serves as the equivalent of the "third region" described above. In certain embodiments of the sensor head, the multi-region membrane further includes an oxygen antenna domain. Each of these domains will now be described in further detail.

#### i. Cell Disruptive Domain

The domain of the multi-region membrane positioned most distal to the electrochemically reactive surfaces corresponds to the cell disruptive domain. This domain includes a material that supports tissue in-growth and may be vascularized. The cell disruptive domain prevents formation of the barrier cell layer on the surface of the membrane, which as described above, blocks the transport of glucose into the sensor device. A useful cell disruptive domain is described in a U.S. application entitled "Membrane for use with Implantable Devices" which was filed on the same day as the present application. The cell disruptive domain may be composed of an open-cell configuration having cavities and solid portions. Cells may enter into the cavities, however, they can not travel through or wholly exist within the solid portions. The cavities allow most substances to pass through, including, e.g., macrophages.

The open-cell configuration yields a co-continuous solid domain that contains greater than one cavity in three dimensions substantially throughout the entirety of the membrane. In addition, the cavities and cavity interconnections may be formed in layers having different cavity dimensions.

A linear line can be used to define a dimension across a cavity or solid portion the length of which is the distance between two points lying at the interface of the cavity and solid portion. In this way, a substantial number of the cavities are not less than 20 microns in the shortest dimension and not more than 1000 microns in the longest dimension. Preferably, a substantial number of the cavities are not less than 25 microns in the shortest dimension and not more than 500 microns in the longest dimension.

Furthermore, the solid portion has not less than 5 microns in a substantial number of the shortest dimensions and not more than 2000 microns in a substantial number of the longest dimensions. Preferably, the solid portion is not less than 10 microns in a substantial number of the shortest dimensions and not more than 1000 microns in a substantial number of the longest dimensions and most preferably, not less than 10 microns in a substantial number of the shortest dimensions and not more than 400 microns in a substantial number of the longest dimensions.

The solid portion may be made of polytetrafluoroethylene or polyethylene-co-tetrafluoroethylene, for example. Preferably, the solid portion includes polyurethanes or block copolymers and, most preferably, includes silicone.

When non-woven fibers are utilized as the solid portion of the present invention, the non-woven fibers may be greater than 5 microns in the shortest dimension. Preferably, the non-woven fibers are about 10 microns in the shortest dimension and most preferably, the non-woven fibers are greater than or equal to 10 microns in the shortest dimension.

The non-woven fibers may be constructed of polypropylene (PP), polyvinylchloride (PVC), polyvinylidene fluoride (PVDF), polybutylene terephthalate (PBT), polymethylmethacrylate (PMMA), polyether ether ketone (PEEK), polyurethanes, cellulosic polymers, polysulfones, and block copolymers thereof including, for example, di-block, tri-block, alternating, random and graft copolymers (block copolymers are discussed in U.S. Pat. Nos. 4,803,243 and 4,686,044, hereby incorporated by reference). Preferably, the non-woven fibers are comprised of polyolefins or polyester or polycarbonates or polytetrafluoroethylene.

A subset of the cell disruptive domain is the oxygen antenna domain. This domain can act as an oxygen reservoir during times of minimal oxygen need and has the capacity to provide on demand a higher oxygen gradient to facilitate oxygen transport across the membrane. This domain may be composed of a material such as silicone, that has higher oxygen solubility than aqueous media so that it concentrates oxygen from the biological fluid surrounding the biointerface membrane. This enhances function in the enzyme reaction domain and at the counter electrode surface when glucose conversion to hydrogen peroxide in the enzyme domain consumes oxygen from the surrounding domains. Thus, this ability of the oxygen antenna domain to apply a higher flux of oxygen to critical domains when needed improves overall sensor function. Preferably, this domain is composed of silicone and has a thickness of about 100 microns.

The thickness of the cell disruptive domain is usually not less than about 20 microns and not more than about 2000 microns.

#### ii. Cell Impermeable Domain

The cell impermeable of the first region is positioned less distal to the electrochemically reactive surfaces than the cell disruptive domain of the same region. This domain is impermeable to host cells, such as macrophages. Cell impermeable domains are described in U.S. Pat. No. 6,001,067, herein incorporated by reference, and in copending, commonly owned U.S. application entitled "Membrane for use with Implantable Devices", Ser. No. 09/916,386, filed on even date herewith. The inflammatory response that initiates and sustains a FBC is associated with disadvantages in the practice of sensing analytes. Inflammation is associated with invasion of inflammatory response cells (e.g. macrophages) which have the ability to overgrow at the interface and form barrier cell layers, which may block transport of glucose across the bio-interface membrane. These inflammatory cells may also biodegrade many artificial biomaterials (some of which were, until recently, considered nonbiodegradable). When activated by a foreign body, tissue macrophages degranulate, releasing from their cytoplasmic myeloperoxidase system hypochlorite (bleach) and other oxidative species. Hypochlorite and other oxidative species are known to break down a variety of polymers, including ether based polyurethanes, by a phenomenon referred to as environmental stress cracking. Alternatively, polycarbonate based polyurethanes are believed to be resistant to environmental stress cracking and have been termed biodurable. In addition, because hypochlorite and other oxi-

dizing species are short-lived chemical species in vivo, biodegradation will not occur if macrophages are kept a sufficient distance from the enzyme active membrane.

The present invention contemplates the use of cell impermeable biomaterials of a few microns thickness or more (i.e., a cell impermeable domain) in most of its membrane architectures. This domain of the biointerface membrane is permeable to oxygen and may or may not be permeable to glucose and is constructed of biodegradable materials (e.g. for period of several years in vivo) that are impermeable by host cells (e.g. macrophages) such as for example polymer blends of polycarbonate based polyurethane and PVP.

The thickness of the cell impermeable domain is not less than about 10 microns and not more than about 100 microns.

#### iii. Glucose Exclusion Domain

The glucose exclusion domain includes a thin, hydrophobic membrane that is non-swallowable and blocks diffusion of glucose while being permeable to oxygen. The glucose exclusion domain serves to allow analytes and other substances that are to be measured or utilized by the sensor to pass through, while preventing passage of other substances. Preferably, the glucose exclusion domain is constructed of a material such as, for example, silicone.

The glucose exclusion domain has a preferred thickness not less than about 130 microns, more preferably not less than about 5 and not more than about 75 microns and most preferably not less than 15 microns and not more than about 50 microns.

#### iv. Resistance Domain

In one embodiment of the sensor head the "third region" or "further region" of the multi-region membrane includes a resistance domain. When present, the resistance domain is located more distal to the electrochemically reactive surfaces relative to other domains in this region. As described in further detail below, the resistance domain controls the flux of oxygen and glucose to the underlying enzyme domain. There is a molar excess of glucose relative to the amount of oxygen in samples of blood. Indeed, for every free oxygen molecule in extracellular fluid, there are typically more than 100 glucose molecules present [Updike et al., *Diabetes Care* 5:207-21(1982)]. However, an immobilized enzyme-based sensor using oxygen ( $O_2$ ) as cofactor must be supplied with oxygen in non-rate-limiting excess in order to respond linearly to changes in glucose concentration, while not responding to changes in oxygen tension. More specifically, when a glucose-monitoring reaction is oxygen-limited, linearity is not achieved above minimal concentrations of glucose. Without a semipermeable membrane over the enzyme domain, linear response to glucose levels can be obtained only up to about 40 mg/dL; however, in a clinical setting, linear response to glucose levels are desirable up to at least about 500 mg/dL.

The resistance domain includes a semipermeable membrane that controls the flux of oxygen and glucose to the underlying enzyme domain (i.e., limits the flux of glucose), rendering the necessary supply of oxygen in non-rate-limiting excess. As a result, the upper limit of linearity of glucose measurement is extended to a much higher value than that which could be achieved without the resistance domain. The devices of the present invention contemplate resistance domains including polymer membranes with oxygen-to-glucose permeability ratios of approximately 200:1; as a result, one-dimensional reactant diffusion is adequate to provide excess oxygen at all reasonable glucose and oxygen concentrations found in the subcutaneous matrix [Rhodes et al., *Anal. Chem.*, 66:1520-1529 (1994)].

In preferred embodiments, the resistance domain is constructed of a polyurethane urea/polyurethane-block-polyeth-

ylene glycol blend and has a thickness of not more than about 45 microns, more preferably not less than about 15 microns, and not more than about 40 microns and, most preferably, not less than about 20 microns, and not more than about 35 microns.

#### v. Immobilized Enzyme Domain

When the resistance domain is combined with the cell-impermeable domain, it is the immobilized enzyme domain which corresponds to the outermost domain of the "third region" or "further region", i.e. it is located more distal to the electrochemically reactive surfaces as compared to the other domains in this region. In one embodiment, the enzyme domain includes glucose oxidase. In addition to glucose oxidase, the present invention contemplates the use of a domain impregnated with other oxidases, e.g., galactose oxidase or uricase, for an enzyme-based electrochemical glucose sensor to perform well, the sensor's response must neither be limited by enzyme activity nor cofactor concentration. Because enzymes, including glucose oxidase, are subject to deactivation as a function of ambient conditions, this behavior needs to be accounted for in constructing sensors for long-term use.

Preferably, the domain is constructed of aqueous dispersions of colloidal polyurethane polymers including the enzyme. Preferably, the coating has a thickness of not less than about 2.5 microns and not more than about 12.5 microns, preferably about 6.0 microns.

#### vi. Interference Domain

The interference domain in the "third region" or "further region" is located less distant from the electrochemically reactive surfaces than the immobilized enzyme domain in this same region. It includes a thin membrane that can limit diffusion of molecular weight species greater than 34 kD. The interference domain serves to allow analytes and other substances that are to be measured by the electrodes to pass through, while preventing passage of other substances, including potentially interfering substances. The interference domain is preferably constructed of a polyurethane.

The interference domain has a preferred thickness of not more than about 5 microns, more preferably not less than about 0.1 microns, and not more than about 5 microns and, most preferably, not less than about 0.5 microns, and not more than about 3 microns.

#### vii. Hydrogel Domain

The hydrogel domain is located adjacent to the electrochemically reactive surfaces. To ensure electrochemical reaction, the hydrogel domain includes a semipermeable coating that maintains hydrophilicity at the electrode region of the sensor interface. The hydrogel domain enhances the stability of the interference domain of the present invention by protecting and supporting the membrane that makes up the interference domain. Furthermore, the hydrogel domain assists in stabilizing operation of the device by overcoming electrode start-up problems and drifting problems caused by inadequate electrolyte. The buffered electrolyte solution contained in the hydrogel domain also protects against pH-mediated damage that may result from the formation of a large pH gradient between the hydrophobic interference domain and the electrode (or electrodes) due to the electrochemical activity of the electrode(s).

Preferably, the hydrogel domain includes a flexible, water-swallowable, substantially solid gel-like film having a "dry film" thickness of not less than about 2.5 microns and not more than about 12.5 microns; preferably, the thickness is about 6.0 microns. "Dry film" thickness refers to the thickness of a cured film cast from a coating formulation onto the surface of the membrane by standard coating techniques

13

Suitable hydrogel domains are formed of a curable copolymer of a urethane polymer and a hydrophilic film-forming polymer. Particularly preferred coatings are formed of a polyurethane polymer having anionic carboxylate functional groups and non-ionic hydrophilic polyether segments, which is crosslinked in the presence of polyvinylpyrrolidone and cured at a moderate temperature of about 50° C.

#### B. Electrolyte Phase

The electrolyte phase is a free-fluid phase including a solution containing at least one compound, usually a soluble chloride salt, that conducts electric current. The electrolyte phase flows over the electrodes and is in contact with the hydrogel domain. The devices of the present invention contemplate the use of any suitable electrolyte solution, including standard, commercially available solutions.

Generally speaking, the electrolyte phase should have the same or less osmotic pressure than the sample being analyzed. In preferred embodiments of the present invention, the electrolyte phase includes normal saline.

#### C. Membrane Architectures

Prior art teaches that an enzyme containing membrane that resides above an amperometric electrochemical sensor can possess the same architecture throughout the electrode surfaces. However, the function of converting glucose into hydrogen peroxide by glucose oxidase may only be necessary above the working electrode. In fact, it may be beneficial to limit the conversion of glucose into hydrogen peroxide above the counter electrode. Therefore, the present invention contemplates a number of membrane architectures that include a multi-region membrane wherein the regions include at least one domain.

Referring now to FIG. 2A, which shows one desired embodiment of the general architecture of a three region membrane, first region 33 is permeable to oxygen and glucose and includes a cell disruptive domain distant from the electrodes and a cell impermeable domain less distant from the electrodes. The second region 31 is permeable to oxygen and includes a glucose exclusion domain and region three 32 includes a resistance domain, distant from the electrochemically reactive surfaces, an immobilized enzyme domain less distant from the electrochemically reactive surfaces, an interference domain less distant from the electrochemically reactive surfaces than the immobilized enzyme and a hydrogel domain adjacent to the electrochemically reactive surfaces. The multi-region membrane is positioned over the sensor interface 30 of the non-conductive body 10, covering the working electrode 21, the reference electrode 20 and the counter electrode 22. The electrodes are brazed to the sensor head and back filled with epoxy 28.

In FIG. 2B, the glucose exclusion domain has been positioned over the electrochemically reactive surfaces such that it does not cover the working electrode 21. To illustrate this, a hole 35 has been created in the second region 31 and positioned directly above the working electrode 21. In this way, glucose is blocked from entering the underlying enzyme membrane above the counter electrode 22 and O<sub>2</sub> is conserved above the counter electrode because it is not being consumed by the glucose oxidation reaction. The glucose-blocking domain is made of a material that allows sufficient O<sub>2</sub> to pass to the counter electrode. The glucose-blocking domain may be made of a variety of materials such as silicone or silicone containing copolymers. Preferably, the glucose-blocking domain is made of silicone.

In FIG. 2C, the multi-region membrane is shown as being constructed of two regions: a first region 33 which includes a cell disruptive domain and a cell impermeable domain; and a further region 32. Region 32 is defined herein as including an

14

enzyme immobilized domain, interference domain, and hydrogel domain and may also include a resistance domain. Region 32 is referred to as the "third region" in embodiments where the multi-region membrane includes three regions. In the embodiment shown, a silicone domain plug 36 positioned over the counter electrode 22 in order to eliminate the consumption of O<sub>2</sub> above the counter electrode by the oxidation of glucose with glucose oxidase. The enzyme immobilized domain can be fabricated as previously described, then a hole punched into the domain. The silicone domain plug 36 may be cut to fit the hole, and then adhered into place, for example, with silicone adhesive (e.g., MED-1511, NuSil, Carpinteria, Calif.).

In FIG. 2D, the immobilized enzyme domain of the multi-region membrane can be fabricated such that active enzyme 37 is positioned only above the working electrode 21. In this architecture, the immobilized enzyme domain may be prepared so that the glucose oxidase only exists above the working electrode 21. During the preparation of the multi-region membrane, the immobilized enzyme domain coating solution can be applied as a circular region similar to the diameter of the working electrode. This fabrication can be accomplished in a variety of ways such as screen printing or pad printing. Preferably, the enzyme domain is pad printed during the enzyme membrane fabrication with equipment as available from Pad Print Machinery of Vermont (Manchester, Vt.). These architectures eliminate the consumption of O<sub>2</sub> above the counter electrode 22 by the oxidation of glucose with glucose oxidase.

In FIG. 2E, the immobilized enzyme of the multi-region membrane in region 32 may be deactivated 38 except for the area covering the working electrode 21. In some of the previous membrane architectures, the glucose oxidase is distributed homogeneously throughout the immobilized enzyme domain. However, the active enzyme need only reside above the working electrode. Therefore, the enzyme may be deactivated 38 above the counter 22 and reference 20 electrodes by irradiation. A mask that covers the working electrode 21, such as those used for photolithography can be placed above the membrane. In this way, exposure of the masked membrane to ultraviolet light deactivates the glucose oxidase in all regions except that covered by the mask.

FIG. 2F shows an architecture in which the third region 32 which includes immobilized enzyme only resides over the working electrode 21. In this architecture, consumption of O<sub>2</sub> above the counter electrode 22 by the oxidation of glucose with glucose oxidase is eliminated.

#### D. The Electrode Assembly

The electrode assembly of this invention comprises a non-conductive body and three electrodes affixed within the body having electrochemically reactive surfaces at one location on the body and an electronic connection means at another location on the body and may be used in the manner commonly employed in the making of amperometric measurements. A sample of the fluid being analyzed is placed in contact with a reference electrode, e.g., silver/silver-chloride, a working electrode which is preferably formed of platinum, and a counter electrode which is preferably formed of gold or platinum. The electrodes are connected to a galvanometer or polarographic instrument and the current is read or recorded upon application of the desired D.C. bias voltage between the electrodes.

The ability of the present device electrode assembly to accurately measure the concentration of substances such as glucose over a broad range of concentrations in fluids including undiluted whole blood samples enables the rapid and accurate determination of the concentration of those sub-

stances. That information can be employed in the study and control of metabolic disorders including diabetes.

The present invention contemplates several structural architectures that effectively increase the electrochemically reactive surface of the counter electrode. In one embodiment, the diameter of wire used to create the counter electrode is at least twice the diameter of the working electrode. In this architecture, it is preferable that the electrochemically reactive surface of the counter electrode be not less than about 2 and not more than about 100 times the surface area of the working electrode. More preferably, the electrochemically reactive surface of the counter electrode is not less than about 2 and not more than about 50, not less than about 2 and not more than about 25 or not less than about 2 and not more than about 10 times the surface area of the working electrode. In another embodiment, the electrochemically reactive surface is larger than the wire connecting this surface to the sensor head. In this architecture, the electrode could have a cross-sectional view that resembles a "T". The present invention contemplates a variety of configurations of the electrode head that would provide a large reactive surface, while maintaining a relatively narrow connecting wire. Such configurations could be prepared by micromachining with techniques such as reactive ion etching, wet chemical etching and focused ion beam machining as available from Norsam Technologies (Santa Fe, N. Mex.).

In another embodiment, the diameter of the counter electrode is substantially similar to the working electrode; however, the surface of the counter electrode has been modified to increase the surface area such that it has at least twice the surface area of the working electrode. More specifically the counter electrodes surface may be textured, effectively increasing its surface area without significantly increasing its diameter. This may be accomplished by a variety of methods known to those skilled in the art including, such as acid etching. The electrochemically reactive surface may be provided in a variety of shapes and sizes (e.g. round, triangular, square or free form) provided that it is at least twice the surface area of the working electrode.

In all of the architectures described, the electrodes are prepared from a 0.020" diameter wire having the desired modified reactive surface. The electrodes are secured inside the non-conductive body by brazing. The counter electrode is preferably made of gold or platinum.

### III. Analyte Measuring Device

A preferred embodiment of an analyte measuring device including a sensor head according to the present invention is shown in FIG. 6A. In this embodiment, a ceramic body 1 and ceramic head 10 houses the sensor electronics that include a circuit board 2, a microprocessor 3, a battery 4, and an antenna 5. Furthermore, the ceramic body 1 and head 10 possess a matching taper joint 6 that is sealed with epoxy. The electrodes are subsequently connected to the circuit board via a socket 8.

As indicated in detail in FIG. 6B, three electrodes protrude through the ceramic head 10, a platinum working electrode 21, a platinum counter electrode 22 and a silver/silver chloride reference electrode 20. Each of these is hermetically brazed 26 to the ceramic head 10 and further secured with epoxy 28. The sensing region 24 is covered with a multi-region membrane described above and the ceramic head 10 contains a groove 29 so that the membrane may be affixed into place with an o-ring.

### IV. Experimental

The following examples serve to illustrate certain preferred embodiments and aspects of the present invention and are not to be construed as limiting the scope thereof

In the preceding description and the experimental disclosure which follows, the following abbreviations apply: Eq and Eqs (equivalents); mEq (milliequivalents); M (molar); mM (millimolar);  $\mu$ M (micromolar); N (Normal); mol (moles); mmol (millimoles);  $\mu$ mol (micromoles); nmol (nanomoles); g (grams); mg (milligrams);  $\mu$ g (micrograms); Kg (kilograms); L (liters); mL (milliliters); dL (deciliters);  $\mu$ L (microliters); cm (centimeters); mm (millimeters);  $\mu$ m (micrometers); nm (nanometers); h and hr (hours); min. (minutes); s and sec. (seconds); ° C. (degrees Centigrade); Astor Wax (Titusville, Pa.); BASF Wyandotte Corporation (Parsippany, N.J.); Data Sciences, Inc. (St. Paul, Minn.); DuPont (DuPont Co., Wilmington, Del.); Exxon Chemical (Houston, Tex.); GAF Corporation (New York, N.Y.); Markwell Medical (Racine, Wis.); Meadox Medical, Inc. (Oakland, N.J.); Mobay (Mobay Corporation, Pittsburgh, Pa.); NuSil Technologies (Carpenteria, Calif.) Sandoz (East Hanover, N.J.); and Union Carbide (Union Carbide Corporation; Chicago, Ill.).

### EXAMPLE 1

#### Preparation of the Multi-Region Membrane

##### A. Preparation of the First Region

The cell disruptive domain may be an ePTFE filtration membrane and the cell impermeable domain may then be coated on this domain layer. The cell impermeable domain was prepared by placing approximately 706 gm of dimethylacetamide (DMAC) into a 3 L stainless steel bowl to which a polycarbonateurethane solution (1325 g, Chronoflex AR 25% solids in DMAC and 5100 cp) and polyvinylpyrrolidone (125 g, Plasdone K-90 D) are added. The bowl was then fitted to a planetary mixer with a paddle type blade and the contents were stirred for 1 hour at room temperature. This solution was then coated on the cell disruptive domain by knife edge drawn at a gap of 0.006" and dried at 60° C. for 24 hours.

Alternatively, the polyurethane polyvinylpyrrolidone solution prepared above can be coated onto a PET release liner using a knife over roll coating machine. This material is then dried at 305° F. for approximately 2 minutes. Next the ePTFE membrane is immersed in 50:50 (w/v) mixture of THF/DMAC and then placed atop the coated polyurethane polyvinylpyrrolidone material. Light pressure atop the assembly intimately embeds the ePTFE into the polyurethane polyvinylpyrrolidone. The membrane is then dried at 60° C. for 24 hours.

##### B. Preparation of the Glucose Exclusion Domain

An oxime cured silicone dispersion (NuSil Technologies, MED-6607) was cast onto a polypropylene sheet and cured at 40° C. for three days.

##### C. Preparation of the Third Region

The "third region" or "further region" includes a resistance domain, an immobilized enzyme domain, an interference domain and a hydrogel domain. The resistance domain was prepared by placing approximately 281 gm of dimethylacetamide into a 3 L stainless steel bowl to which a solution of polyetherurethaneurea (344 gm of Chronothane H, 29,750 cp at 25% solids in DMAC). To this mixture was added another polyetherurethaneurea (312 gm, Chronothane 1020, 6275 cp at 25% solids in DMAC.) The bowl was fitted to a planetary mixer with a paddle type blade and the contents were stirred for 30 minutes at room temperature. The resistance domain coating solutions produced is coated onto a PET release liner (Douglas Hansen Co., Inc. Minneapolis, Minn.) using a knife over roll set at a 0.012" gap. This film is then dried at 305° F. The final film is approximately 0.0015" thick.

17

The immobilized enzyme domain was prepared by placing 304 gm polyurethane latex (Bayhydrol 140 AQ, Bayer, Pittsburgh, Pa.) into a 3 L stainless steel bowl to which 51 gm of pyrogen free water and 5.85 gm of glucose oxidase (Sigma type VII from *Aspergillus niger*) is added. The bowl was then fitted to a planetary mixer with a whisk type blade and the mixture was stirred for 15 minutes. Approximately 24 hr prior to coating a solution of glutaraldehyde (15.4 mL of a 2.5% solution in pyrogen free water) and 14 mL of pyrogen free water was added to the mixture. The solution was mixed by inverting a capped glass bottle by hand for about 3 minutes at room temperature. This mixture was then coated over the resistance domain with a #10 Mayer rod and dried above room temperature preferably at about 50° C.

The interference domain was prepared by placing 187 gm of tetrahydrofuran into a 500 mL glass bottle to which an 18.7 gm aliphatic polyetherurethane (Tecoflex SG-85A, Thermomedics Inc., Woburn, Mass.) was added. The bottle was placed onto a roller at approximately 3 rpm within an oven set at 37° C. The mixture was allowed to roll for 24 hr. This mixture was coated over the dried enzyme domain using a flexible knife and dried above room temperature preferably at about 50° C.

The hydrogel domain was prepared by placing 388 gm of polyurethane latex (Bayhydrol 123, Bayer, Pittsburgh, Pa. in a 3 L stainless steel bowl to which 125 gm of pyrogen free water and 12.5 gm polyvinylpyrrolidone (Plasdone K-90D) was added. The bowl was then fitted to a planetary mixer with a paddle type blade and stirred for 1 hr at room temperature. Within 30 minutes of coating approximately 13.1 mL of carbodiimide (UCARLNK) was added and the solution was mixed by inverting a capped polyethylene jar by hand for about 3 min at room temperature. This mixture was coated over the dried interference domain with a #10 Mayer rod and dried above room temperature preferably at about 50° C.

In order to affix this multi-region membrane to a sensor head, it is first placed into buffer for about 2 minutes. It is then stretched over the nonconductive body of sensor head and affixed into place with an o-ring.

## EXAMPLE 2

### In Vitro Evaluation of Sensor Devices

This example describes experiments directed at sensor function of several sensor devices contemplated by the present invention.

In vitro testing of the sensor devices was accomplished in a manner similar to that previously described. [Gilligan et al., Diabetes Care 17:882-887 (1994)]. Briefly, devices were powered on and placed into a polyethylene container containing phosphate buffer (450 ml, pH 7.30) at 37° C. The container was placed onto a shaker (Lab Line Rotator, model 1314) set to speed 2. The sensors were allowed to equilibrate for at least 30 minutes and their output value recorded. After this time, a glucose solution (9.2 ml of 100 mg/ml glucose in buffer) was added in order to raise the glucose concentration to 200 mg/dl within the container. The sensors were allowed to equilibrate for at least 30 minutes and their output value recorded. Again, a glucose solution (9.4 ml of 100 mg/ml glucose in buffer) was added in order to raise the glucose concentration to 400 mg/dl within the container. The sensors were allowed to equilibrate for at least 30 minutes and their output value recorded. In this way, the sensitivity of the sensor to glucose is given as the slope of sensor output versus glucose concentration. The container was then fitted with an O<sub>2</sub> meter (WTW, model Oxi-340) and a gas purge. A mixture of compressed air and nitrogen was used to decrease the O<sub>2</sub>

18

concentration. Sensor output was recorded at an ambient O<sub>2</sub> level, then sensor output was recorded for the following O<sub>2</sub> concentrations; 1 mg/L, 0.85 to 0.75 mg/L, 0.65 to 0.55 mg/L and 0.40 to 0.30 mg/L. In this way, the function of the sensor could be compared to its function at ambient O<sub>2</sub>.

Sensor devices like the one shown in FIGS. 6A and 6B, which included inventive sensor heads having a multi-region membrane with the architecture shown in FIG. 2B, were tested in vitro. Eight of these devices were fitted with membranes that possessed a 0.020" diameter hole, four with a 0.0015" thick polyurethane (Chronoflex AR, CardioTech International Inc.) and four with a 0.032" thick silicone (MED-1511, NuSil Technologies Inc.). The hole was positioned above the working electrode and both membranes were secured to the device with an o-ring. Four control devices were also tested which were fitted with a multi-region membrane which lacked region 31 shown in FIG. 2B.

As discussed above, for oxygen to be consumed in the sensing region 32 above the electrodes, glucose is required. By placing region 31 shown in FIG. 2B, which includes a glucose blocking domain, above all areas other than above the working electrode 21, oxygen consumption in areas other than working electrode areas is limited. In contrast, by eliminating region 31 in the control devices, less overall oxygen becomes available to electrode surfaces due to the increased availability of glucose.

The devices were activated, placed into a 500 ml-polyethylene container with sodium phosphate buffered solution (300 ml, pH 7.3) and allowed to equilibrate. Each device's baseline value was recorded. Then 12 ml of glucose solution (100 mg/ml in sodium phosphate buffer) was added to the container so that the total glucose concentration became 400 mg/dL. After this, the container was covered and fitted with an oxygen sensor and a source of nitrogen and compressed air. In this way, the oxygen concentration was controlled with a gas sparge. A glucose value was recorded for each device at decreasing oxygen concentrations from ambient to approximately 0.1 mg/L.

FIG. 7 graphically represents the formation of a device of the present invention utilizing the multi-region membrane architecture in FIG. 2B in vitro. The data is expressed in percent Device Function at 400 mg/dL glucose vs. oxygen concentration. The percent function of the device is simply the device output at any given oxygen concentration divided by that device's output at ambient oxygen. The results from FIG. 7 indicate that inventive sensor devices containing the silicone membrane have better function at lower oxygen concentrations relative to both the control devices and the devices containing the polyurethane membrane. For example, at an oxygen concentration of about 0.5 mg/L, devices containing the silicone membrane are providing 100% output as compared to 80% output for the control devices.

## EXAMPLE 3

### The Effect of Varying the Size and Material of the Counter Electrode on Sensor Response and Accuracy

An in vitro testing procedure used in this example was similar to that described in Example 2. Six devices similar to the one shown in FIGS. 6A and 6B were fitted with the multi-region membrane described herein. Two of these tested devices were comparative devices that possessed Pt counter electrodes having a 0.020" diameter; this diameter provided for an electrochemically reactive surface of the counter electrode which was substantially equal to the surface area of the working electrode, as schematically shown in FIG. 8. In FIG.



8, the electrode-membrane region includes two distinct regions, the compositions and functions of which have already been described. Region 32 includes an immobilized enzyme. Region 33 includes a cell disruptive domain and a cell impermeable domain. The top ends of electrodes 21 (working), 20 (reference) and 22 (counter) are in contact with an electrolyte phase 30, a free-flowing phase. Two other tested devices possessed Pt counter electrodes having a 0.060" diameter. Finally, two additional devices possessed Au counter electrodes having a 0.060" diameter. The 0.006" diameter devices provided for an electrochemically reactive surface of the counter electrode which was approximately six times the surface area of the working electrode. Each of the devices including counter electrodes of 0.060" diameter include a multi-region membrane above the electrode region which is similar to that shown in FIG. 8.

The devices were activated, placed into a 500 ml-polyethylene container with sodium phosphate buffered solution (300 ml, pH 7.3) and allowed to equilibrate. Each device's baseline value was recorded. Then 12 ml of glucose solution (100 mg/ml in sodium phosphate buffer) was added to the container so that the total glucose concentration became 400 mg/dL. After this, the container was covered and fitted with an oxygen sensor and a source of nitrogen and compressed air. In this way, the oxygen concentration was controlled with a gas sparge. A counter electrode voltage was recorded for each device at decreasing oxygen concentrations from ambient to approximately 0.1 mg/L.

FIG. 9 graphically presents the counter electrode voltage as a function of oxygen concentration and 400 mg/dL glucose. This figure demonstrates that both the large Pt and Au counter electrode devices do not begin to reach the circuitry limits at low oxygen concentrations. Therefore, increased performance and accuracy can be obtained from a counter electrode that has an electrochemical reactive surface greater than the surface area of the working electrode.

The description and experimental materials presented above are intended to be illustrative of the present invention while not limiting the scope thereof. It will be apparent to those skilled in the art that variations and modifications can be made without departing from the spirit and scope of the present invention.

What is claimed is:

1. An implantable continuous glucose sensor system configured for implantation in a host, the system comprising:
  - an electrode comprising an electroactive surface, wherein the electrode is configured for implantation and is configured to generate in vivo a signal indicative of glucose concentration in a host;
  - a membrane comprising:
    - a first domain configured to reduce a flux of glucose therethrough;
    - a second domain comprising an enzyme configured to react with glucose to produce a measured species, wherein the second domain is located less distant to the electroactive surface than the first domain; and
    - a third domain comprising an architecture that permits access to the electroactive surface only for species that have a molecular weight less than or about equal to a molecular weight of the measured species, wherein the third domain is located less distant to the electroactive surface than the second domain; and
  - sensor electronics operably connected to the electrode and configured to measure the signal from the electrode.
2. The implantable continuous glucose sensor of claim 1, wherein the molecular weight of the architecture limits diffusion of species that have a molecular weight more than 34 Daltons.
3. The glucose sensor of claim 1, wherein the first domain comprises a polyurethane.
4. The glucose sensor of claim 1, wherein the first domain is an outermost domain of the membrane.
5. The glucose sensor of claim 1, wherein the first domain is configured to interface with biological fluid.
6. The glucose sensor of claim 1, wherein the electrode is a working electrode, wherein the system further comprises a reference electrode and a counter electrode.
7. The glucose sensor of claim 1, wherein the counter electrode comprises an electroactive surface, wherein the counter electrode electroactive surface has a larger area than an area of the working electrode electroactive surface.

\* \* \* \* \*